Investigations of the Herring of Passamaquoddy and Adjacent Regions

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ABSTRACT

The young herring ("sardine") fishery is seen as partly dependent on extremely local conditions. The fish first appear in the catches when about 12 months old in August. They are generally segregated into shoals of similar length (within an age-group). Certain areas tend to have herring of particular sizes. The "sardine" region is poorly supplied with herring fry rather than well supplied. Turbidity of the water is the only physical factor found possibly rendering the region specially attractive to herring. Euphausiids at the surface are one of the striking features of the heart of the "sardine" region. The principal species of plankton animals (*Thysanoessa, Calanus, Sagitta*) behave in a manner best explained by diurnal quiescence and nocturnal activity. Large landings of "sardines" in the "sardine" region as compared with other places is partly to be explained as due to especial ease of capture in that region, but it is uncertain whether there is a larger population of fish. It is clear that the proposed dams across the mouths of Passamaquoddy and Cobscook bays would make considerable havoc of the exceptionally rich fishery in their neighbourhood. The fishery inside the dams would almost certainly be reduced to negligible proportions, since it seems dependent on immigration. It cannot be foretold whether the total effect on capture immediately outside the dams would be deleterious or not. There appears little possibility of a wide-spread effect, for example along the coast of Maine, or even seriously at Grand Manan.

I. NARRATIVE

Under the International Passamaquoddy Fisheries Commission, an investigation was undertaken in connection with the proposal to install power dams across the mouths of Passamaquoddy and Cobscook bays at the international boundary between the province of New Brunswick and the state of Maine. The results obtained for the phytoplankton have already been published (Gran and Braarud 1935). Papers on the hydrography and the zooplankton are to follow.

The fishery side of the investigation was mainly concerned with the herring, the most important commercial species in Charlotte and Washington counties.* The period from September 1931 to November 1932 was spent in the field of observation, with a base at St. Andrews. Inquiries on a preliminary tour of the coast from Portland to Halifax revealed the necessity of observations on the

*Most of the place names may be found either on figure 5 or on figure 9.

very young herring, at the stage when they are mainly moved with the water currents, and it seemed that these observations should extend as far as possible in the bay of Fundy and to eastward and westward. The correct season was the winter, and for this purpose the motor vessel, the "Nova IV" was used to make 323 hauls of a suitable net from the 11th of December to the 29th of June. The area of observation extended from the head of the bay of Fundy to the vicinity of Boston, to Brown's bank and as far east as Liverpool, Nova Scotia. Similar observations were made from the U.S. vessel "Pelican" towards the end of September 1932 in the mouth of the bay of Fundy.

The "Pelican" was used during July 1932 to obtain 47 observations on transparency and surface temperature near the coast of Maine, Fundy and Nova Scotia.

The remainder of the time was occupied in verbal inquiries among fishermen and other people concerned with the fishery, with the examination of material collected at sea and the collection of supplementary material at the coast, and with organisation of collection of special statistics of purchases of sardines by canneries, daily news of the whereabouts of sardines, measurements of length and particulars of weir operation. For these inquiries the motor boat "Prince" was used extensively. A special short cruise was made in connection with an extraordinary fishery that occurred in Maces bay at the time. For this cruise and other work, the Canadian Government vessel "Phalarope" was very kindly loaned.

During the winter of 1932-1933 the information collected was tabulated and arranged, and the published statistics were also studied.

During the greater part of the time in Canada and the United States I had the valuable assistance of Mr. James Bates. Acknowledgement should be made of the assistance not only of my colleagues on the commission staff, but also of Dr. A. G. Huntsman and the staff of the Biological Board of Canada at St. Andrews. In addition special mention must be made of the degree to which Inspectors of the Department of Fisheries have helped me, under instructions kindly given by Dr. W. A. Found. Acknowledgement is also due to the captains and crews of the vessels used, especially Captain Albert Moore of the "Nova IV" and his crew, who cheerfully undertook the arduous duties involved in our winter observations.

In the semi-statistical inquiries we had the valuable co-operation of three canning companies, Connors Bros. of Blacks Harbour, the R. J. Peacock Company of Lubec and the Union Sardine Company of Lubec.

Tables giving details of the sea observations are on file with the Biological Board of Canada.

The following gear was used in making observations and collections.

Petersen net

The Petersen net was made of stramin about 15 threads to the inch (2.5 cm.) and about half of every inch made up of threads (making the lumina about 1/30 inch square (0.72 sq. mm.), *when dry*). It was mounted on an iron ring

and towed on two bridles. A weight was suspended from the lowest point of the ring on a strop one fathom (1.8 m.) long.

It was fished for 30 minutes obliquely from bottom to surface, that is, enough wire was let out to allow the net to touch bottom at an angle of 45 degrees; the angle was maintained at 35 to 45 degrees for one third of the 30 minutes, the wire was then shortened to half the previous length and another third of the time fished; the wire was then shortened so as to bring the net within 1-3 fathoms (1.8-5.5 m.) of the surface, and the remainder of the half hour was so fished. According to the depth more or less time was allowed for shortening, which was at the rate of about 12 fathoms (22 m.) of wire per minute.

At thirteen stations the net was fished from surface to bottom, the time, 30 minutes, being divided into 10 intervals, during the first of which the net was fished near the surface, after which enough wire was slacked out to allow it to reach a layer one tenth of the way towards the bottom, and so on.

Metre net (No. XXOOO-XXO)

Fished in the same manner as the Petersen, being led from the Petersen wire itself, but held on a piece of rope 39 fathoms (71.5 m.) of which was in the water, or less where the depth of water did not allow the full length. When the Petersen was raised to midwater the townet rope was shortened to half its length. The aim was an oblique haul from 50-0 metres. The duration was necessarily the same as that of the Petersen, 30 minutes.

Metre net (No. XXOOOO-XXO)

Fished on a ring that was only 80 cm. in diameter. This was fished obliquely from surface to about two-thirds of the depth for 15 minutes, being gradually slacked away. No closing device was used.

Half metre nets (No. 15X)

Fished in the same manner as the metre net (No. XXOOO-XXO).

Bigelow bottle

Used to obtain phytoplankton samples at 1, 10, 25, 40 and 75 metres where the depth allowed. Also used to obtain temperature and sometimes salinity at 25 m.

Iron bucket

Used to obtain surface temperature and sometimes surface salinity. The bucket was soaked over the side for a full minute.

Secci disc

A white enamelled plate 20 cm. in diameter, the reading given being the mean of two, the depth recorded by the metre wheel when the disc became invisible going down, and the reading of the wheel when the disc again became visible on being raised. The disc was watched through a water telescope.

Drift bottles

Drift bottles with four foot (1.2 m.) drags were liberated as follows: July 16, 1932, nos. 455 to 500, at approximately 1 mile (1.6 km.) intervals on a line between 43° 41¾′ N. lat., 64° 40¼′ W. long. and 43° 6½′ N. lat., 64° 6¼′ W. long.; U.S. drift bottles Nos. 4615 to 4621 at 3 mile (4.8 km.) intervals on a line from sta. N241 (42° 38′ lat. 65° 36′ long.) to sta. N242 (42° 59′ lat. 65° 42′ long.); nos. 4622, 4628, 4623-4625 at 4 mile (6.4 km.) intervals from sta. N242 to sta. N243 (43° 16′ lat. 65° 43½′ long.); nos. 4629, 4626, 4627, 4630 to 4634 at sta. N243.

Otter trawl, 15 ft (4.6 m.)

Used at stations 233 and 268. At sta. N233, 10 min. on bottom and 10 min. off bottom.

II. THE SARDINE FISHERY

Dr. Huntsman has repeatedly pointed out that the statistics of landings of herring, including sardine herring, show a marked concentration of landing in Charlotte and Washington counties, which is very clearly seen on the chart prepared by Dr. A. W. H. Needler, reproduced as figure 1 (Huntsman 1928, 1932, 1933, 1934). That chart was prepared for the year 1919 and the statistics for more recent years that are available, 1928-1930, confirm the 1919 picture. The
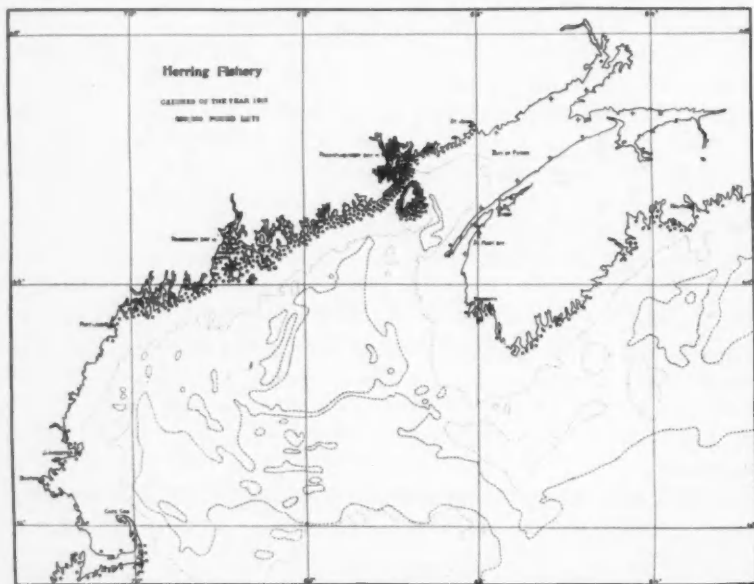
FIGURE 1. Dr. Needler's chart of herring landings. This chart (reproduced by the courtesy of the Biological Board of Canada) was constructed by placing dots opposite each county according to the weight of herring (including sardines) landed in 1919 (information from official U.S. and Canadian statistics). Similar information is given in table II for all years available. The picture for 1919 is found to be valid in the other years examined.

area of this herring fishery may be said to run from cape Spencer to cape Elizabeth, with apparently marked concentration in the Quoddy area. I have attempted some refinement of the same information by dividing the county catches by the length of the coast line, measured on the only chart which takes in the whole area, which, unfortunately, is on the scale of 18 miles (23 km.) to the inch (2.5 cm.). When this is done it does appear that the two areas of greater concentration are about firstly, Washington and Charlotte, and secondly, Knox to Cumberland counties in Maine (table II). It is to be noted that these areas of concentration of landing are each of them west of a great river, namely the Saint John and the Penobscot. This appears to be relevant to an important problem, raised and discussed by Huntsman and Hachey (1934a).

The herring fishery in Charlotte county is of two kinds: the spawning fishery, principally at Grand Manan, and the fishery for immature herring, which are made into sardines. In examining the statistics one may use the figures for sardines alone, or may add them to the figures for herring excluding sardines. In either case one falls into error. Herring of medium size may sometimes be sold to canners and entered as "sardines" and sometimes to smokers and entered as "herring". Other events in the trade may introduce ambiguity, such as canners buying herring larger than they usually like, owing to a scarcity of small fish; or the consignment of large quantities of sardine herring to fertilizer plants. On the other hand, to include the figures for "herring" definitely confuses the spawning fish with the smaller immature fish. On the whole it appears preferable for some purposes to use the statistics for sardines alone, since the errors to which we have called attention are probably without bias and will not usually affect conclusions from averages, whereas the inclusion of mature herring definitely introduces a factor, namely sexual maturity, which we know to be irrelevant, as regards the bulk of the herring which go to make the sardine fishery. From consideration of average figures for such years as we have available (tables III, IV) it is clear that the fishery is in full swing in Charlotte county in May, except for the Grand Manan section, and is still important in October, after which the landings rapidly decline. In Grand Manan and in Saint John county the early part of the season is not so important. In the four divisions of Charlotte county, and in Saint John county, the maximum monthly landing is of the same order of magnitude. We have found by measurements that the coast lines are also of the same order of magnitude (counting Saint John county only as far as cape Spencer because there is little sardine fishery further east), whence it appears that the maximum concentration of landings is not *vastly* different in any part of the New Brunswick side of the mouth of the bay of Fundy. There are, however, differences in the incidence and length of the season and, in our short series of figures, eastern Charlotte seems less productive than the rest. In Charlotte county, excluding Grand Manan, there is some tendency for the May catch to be higher than the June, causing a saddle in the curves of monthly landings. These various details will not now be considered further, since their description really demands a complicated inquiry into the incidence of the variations, and mathematical tests of their significance, work which is not justified from the point of view of the present investigation.

In Charlotte county all the herring are taken in weirs (figure 2 is a photograph of weirs). All weirs are not equally good, in fact it would almost appear that every weir has its own peculiarities. Successful and unsuccessful weirs may be closely adjacent. For example, in a place we may call locality A an inspector described two weirs as among the least successful in his district. They are ⅓ mile (0.5 km.) apart. A circle with ½ mile (0.8 km.) radius drawn round a point half way between them encloses 7 other weirs of which no less than 5 were described by the same inspector as among the most successful. In another place, an open bay B, there are 4 weirs within one mile (1.6 km.). Three were placed in the highly successful category, but the fourth was selected as among the markedly poor ones of the district. Peculiarity of weir-fishing is also seen
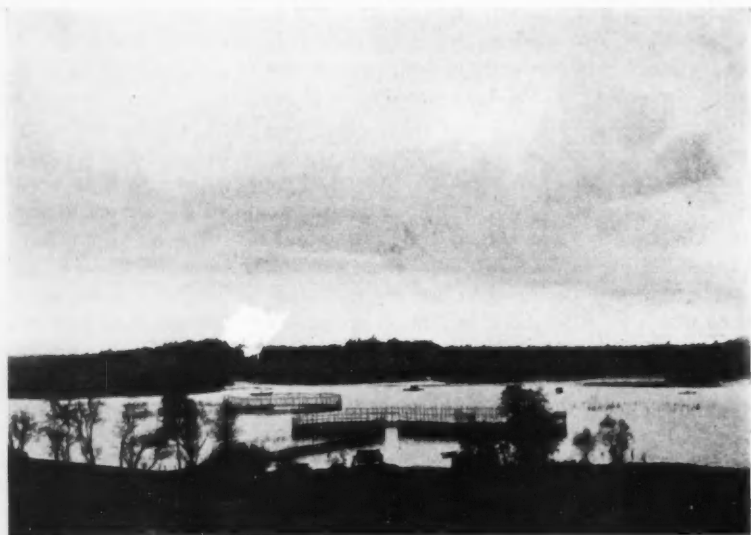
FIGURE 2. Weirs in Harbour de Loutre. Two weirs (central and left) are ready for fishing. Old stakes of a discarded weir are on the right. There is a dummy on the left hand weir to scare cormorants, which are liable to get into the weir and drive the fish out. The object in front of the central weir is a reel mounted on a float. On the reel is wound the purse seine used for taking the fish from the weir. At the right of the weir is the pound, a separate compartment used for retaining herring that are gorged with food, while they digest it; otherwise, presumably owing to autolysis and decay of semi-digested food, the fish will not go through the canning process. The lower part of the weir is of wood and brushwood, and netting, so called "twine", is hung in the upper part.

in seasonal records. For example, the Frye's Island Corporation, whose records were made available to me by the courtesy of Messrs. Connors Bros., operate ten weirs on Frye's Island (Chart names "Cailiff island" and "Payne Island", "Cailiff" being a misspelling, according to Miss Helen Mowat of St. Andrews, who is a descendant of the original Calef). The averages of five years' records of

monthly sales of these weirs are given in table V and shown graphically in figure 3. Positions of the weirs are shown in the chart of figure 4. Eight of the ten weirs show a peak in May (exceptionally April), but this spring fishery is notably absent or poor in "Calef Beach" and "Tarpot". The "Cumberland Shore" weir is consistently the best yielding weir of the ten, but in August and September the monthly sales from "Calef Beach" are of the same order of magnitude as the "Cumberland Shore". No explanation is now tendered of these phenomena, but the facts are given to emphasize the consideration that *this fishery is evidently influenced by factors of which we are profoundly ignorant.* In figure 4 charts are shown, extracted from a collection made of the approximately weekly sales of the same weirs. The whole collection contains many interesting periods, but the one chosen as an example is simpler to describe than
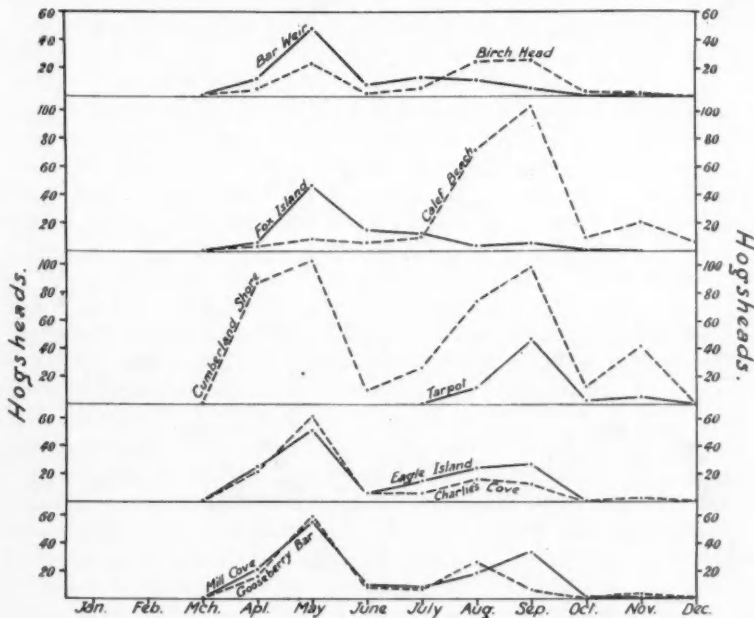
FIGURE 3. Average fishing of Frye's island weirs. The figure shows the average monthly catch for a period of five years (data in table V). The graphs show individual peculiarities, discussed in the text, p. 101.

the others. It is to be observed that at first none of the weirs were fishing, with the exception of a small quantity sold from "Fox Island" (D). Between May 11 and May 14, however, all the weirs from "Cumberland Shore" (G) to the westward took good quantities of herring. Between May 14 and 21 the same distribution of sales is observed, and this persisted up till May 26, with the addition of a small quantity from "Fox Island" (D). Attention is called to two features. In the first place, despite the strong tides of the neighbourhood,
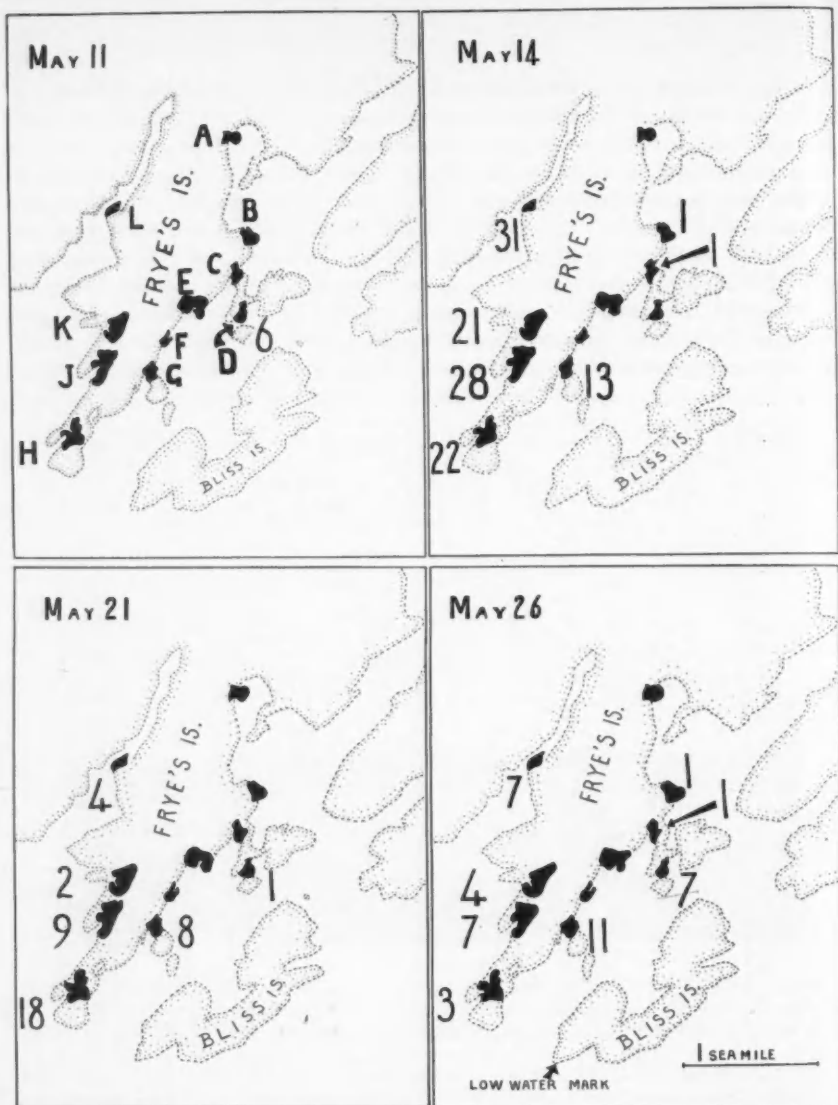
FIGURE 4. Four weeks' fishing of Frye's Island weirs. The four charts are extracted from a collection extending over two seasons. The areas enclosed by the weirs are blacked in and low water mark is shown as a broken line. The numbers give the number of hogsheads sold from each weir. It is to be observed that at first most of the weirs were not fishing, but between May 11 and 14 all the western weirs and the "Cumberland Shore" fished, and that this condition persisted more or less until the week ending May 26, showing some stability of the sardine herring. Two weirs "Calef Beach" and "Tarpot" did not fish, which is usual, these two being good fall weirs, rarely fishing in spring. (Table V and text, p. 101). A "Connors' Beach". B "Birch Head". C. "Bar". D "Fox Island". E "Calef Beach". F "Tarpot". G "Cumberland Shore". H "Eagle Island". J "Charlie's Cove". K "Mill Cove". L "Gooseberry Bar".

there is apparently stability of the sardine herring in relation to the islands. In the second place, the complete failure of "Tarpot" (F) and "Calef Beach" (E) to participate in this fishery is truly remarkable, in view of the fact that they are both within a mile of the productive "Cumberland Shore" (G). We have already seen that this is typical for the spring of the year.

It is abundantly clear that *extremely local conditions influence the catches of herring*, which constitute the total landings. In Passamaquoddy bay the weirs have been closely studied by Huntsman (1934) from the point of view of local conditions. His account is commended to the reader interested in the subject. The present, somewhat bald, account of the fishing at Frye's Island is a less important contribution to the study.

III. MEASUREMENTS OF LENGTH OF SARDINE HERRING

It was thought that light might be thrown on the question of whether the sardine herring of the Quoddy region are to be considered as local, as distinct from being a part of a wide-spread population, by tracing the distribution of herring of characteristic lengths within the area. The same investigation was expected to throw light on the first appearance of young herring in the fishery.

For this purpose two observers measured the length of all the herring in a sample of every consignment reaching two sardine canneries. Altogether the observers measured more than 44,000 specimens in 347 samples. Messrs. Connors Bros. of Blacks Harbour, New Brunswick, the R. J. Peacock Canning Co. of Lubec, Maine, and the E. A. Holmes Packing Co. of Eastport, Maine, kindly allowed this work to be done on their premises.

In default of submitting the entire data, which are cumbersome, an extract is given for the week ending September 17. Table VI gives the statistical area to which the sample was allocated, the length-frequency distribution and the "peaks" determined by inspection. The statistical areas are defined in a table on file and shown in figure 5. There are 50, and the boundaries were drawn as naturally as could be devised. Our data also include the names of the fishermen, but these are now withheld, following a well-established practice. Without the fishermen's names allocation could not have been so precise as it has been. In the majority of cases allocation has been possible to the actual weirs, of which the positions were recorded on a chart. In a proportion of cases allocation had to be to two or more of the numbered statistical areas and, in a few, allocation proved impossible ("N.D." in table VI).

The length frequency distributions were treated by the method of determining approximate modes (and sub-modes) here called "peaks". The word "peak" refers to the shape of the corresponding frequency curve. The chief disadvantage of the method of "peaks" is that the results are not susceptible to mathematical tests of significance, but no better method is known of handling large collections of data such as these, for which the method is extremely suitable and of established efficacy (Graham 1934). The observers appear to have done their work carefully and full reliance is placed on it. There were only two occasions where the records show certainly that they both measured samples from the same weir catch. These results were highly satisfactory. In a Poco-

logan catch the Blacks Harbour observer recorded a sample with a main peak at 18 cm. and a lesser peak at 22 cm., and the Lubec observer's record yielded the same main peak at 18 cm. and a subsidiary peak at 21 cm. In a catch from Fairhaven, Deer Island, samples of both observers showed the same peak, at 19 cm. All these peaks were determined by an assistant who did not know what their significance would be, so that they are without any bias. (0.5 cm. should be added to all figures given. This correction is omitted in the text for the sake of brevity).
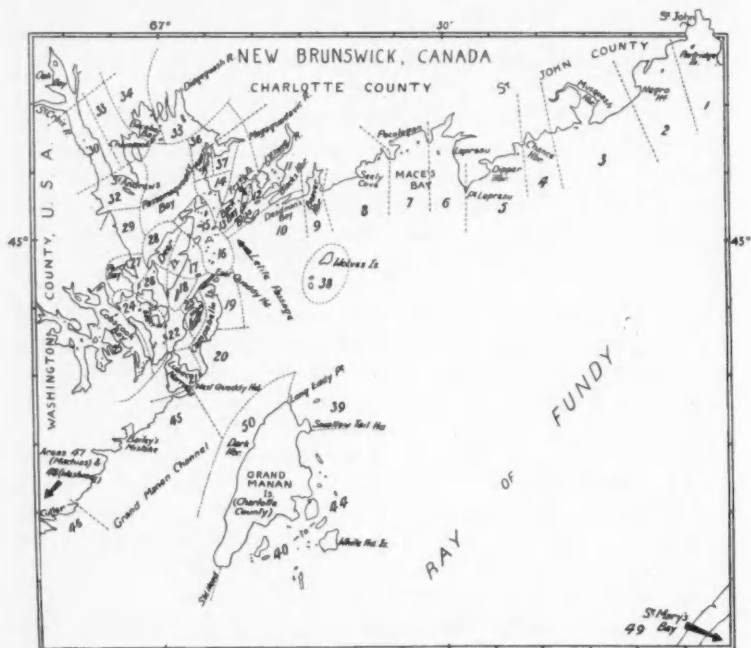
FIGURE 5. The Quoddy region divided into areas for special statistics. The areas shown here have been used in various tables and in figures 6 and 7.

The peaks were then arranged on 19 weekly charts similar to figure 6. In default of submitting them all, we give table VII, from which all the charts may, if desired, be reconstructed. The charts showed several features of interest which will be described.

FIRST APPEARANCE OF SMALLEST SARDINE HERRING

The smallest fish to be canned are no doubt first seen in the collection as very highly selected samples from the population, owing to net selection in the instruments of capture. They appeared in the collection first as 10 cm. fish in the week ending September 3 at St. John and Deer island. Connecting these with those recorded in Sections V and VI we are able to call them about twelve

months old.   Their entry and growth can be followed in table VIII, allowance being made for the masking of growth of the larger by increasing entry of smaller fish.   A peak at 13 cm., attributable to this group, was not common until the end of October.   Peaks at 11 cm. continue to appear until the end of the season. Mr. T. H. Dorr of the U.S. Fish Hatchery at Boothbay, Maine, kindly looked out for such very small herring.   He has sent me measurements of catches made with a drag seine, showing the bulk near $9\frac{1}{2}$ to 10 cm. in September and 10 to 11 cm. in October.

FIGURE 6.   Example of charts showing length of sardine herring.   This chart, referring to the week-ending Sept. 17, is one of 19 made for each week of 1932 from August onwards. Data in table VI.   The numbers show the commonest length, underlined, and sometimes the next most common length (not underlined) in each sample.   These "peak" lengths have been arranged in areas (figure 5).   This particular weekly chart is interesting in showing: (a) the new entrants, at 11 cm., fish about 12 months old, in three areas, (b) the occurrence of particular peaks, 19 amd 24 cm., in widely separated areas, (c) the occurrence of a peak at 17 cm. which is rare throughout the collection, in three different areas.   Immigration is held to account for (b) and (c), and these, with similar observations included in table VII, suggest an extensive body of herring in the more open sea, touching the coast here and there.

DIFFERENTIAL SIZE-DISTRIBUTION

There is manifest a distinct tendency for larger sardine herring to be taken in areas 22 and 23 (Friar Roads and Harbour de Loutre) than elsewhere, although big herrings were by no means confined to those areas (e.g., in week ending

September 10, area 13, Back bay, provided many). Conversely the smallest herring were rarely taken in areas 22 and 23. Otherwise they were liable to occur anywhere, but most commonly in area 15 (eastern Deer island). Generally, however, size was not clearly found to be differentially distributed.

SHOALS OF ONE LENGTH

It is very clear that these sardines are taken in shoals roughly of the same length, and peaks are too close to represent different year groups. Pocologan, for example, area 7, yielded main peaks at 18 or 19 (9 samples) and 21 (one sample) in the week ending September 3; Harbour de Loutre, area 23, had 5 samples with main peak 20 or 21, one $22\frac{1}{2}$ and one 25 in week ending October 1; and many other examples can be found.

INVASION OF AREA FROM ELSEWHERE

The frequent occurrence of shoals of the same length in different areas indicate a widely distributed population, or "main body" whose mass movement affects weirs in many places. Thus in the week ending September 17, the combination of peaks at 19 and 24 in one sample occurred in the following areas: Musquash (area 3), Deer Island (areas 15-16), Mascarene or thereabouts (areas 14, 36 or 37), Grand Manan channel (area 45) and Machias (area 46, 19, 23 and 20, 24 cm.). In the preceding week the combination was taken only in area 7, Pocologan, and the peaks occurred separately only in area 5, Dipper harbour (19, 25), area 13, Back bay (20, 24), and area 46, Machias (19), if indeed these can be called the same peaks. There is a strong suggestion here of an invasion of a very extensive shoal striking the coast at a number of points. Another example is samples with peaks at 15 or 17 in September. Fish of 13 to 18 cm. (which I gather were badly wanted by the factories) were comparatively rare (see table VIII). In the fortnight ending August 20 there were 6 samples with peaks 15 to 17, but these fish seem to have grown to 18 to 19 cm. by September 3; for Pocologan, area 7, yielded the following samples:

Week ending:	Peaks (cm.)
Aug. 13	15, 18.'
20	16, 17, 17, 18.
27	18, $21\frac{1}{2}$.
Sept. 3	18, 18, 18, 18, $18\frac{1}{2}$, $18\frac{1}{2}$, $18\frac{1}{2}$, $18\frac{1}{2}$, 19, 21, 21, 22, 23, 23.

In the week ending September 17, however, such desirable herring with the peak at 17 cm., which we can only believe to be fish not previously sampled, occurred in three places, on the 13th in Bliss or Back bay (area 12-13), on the 16th at Chamcook (area 33), and near Deer island (areas 15, 26 or 28). The week previously 17 cm. had occurred, as a secondary peak, in Dipper (area 5), and in the following week it persisted only as a secondary mode at Chamcook (area 33). This suggests immigration and emigration.

Another example, which is not very definite, but is good supporting evidence, is in the week ending August 27, when we had the following similar peaks:

Area 7. Pocologan *18*, 21½

Area 40-44. Grand Manan, sample (a) *17*, 19, 21

sample (b) 22

Area 1. St. John, sample (a) 16, 19, *21*

sample (b) 18½

sample (c) 18, *22*

Another case of similarity in different areas is:

Week ending September 3:

Area 7. Pocologan *18, 18, 18, 18, 18½, 18½, 18½, 18½, 19, 21*, 21, 22, 23, 23.

Area 46. Machias *19, 19, 19, 19, 19, 19*, 22, 23, 25.

The similarity was continued in the following week.

Another relevant feature is the remarkable rarity of the esteemed and desirable sardine herring of 14 to 17 cm. length. This scarcity was general, which suggests that most of the sardines have been subjected to the same environmental factors, which again suggest an open sea rather than a coastwise habitat.

IV. SPECIAL CANNERY STATISTICS

The official Canadian statistics record the landings of herring and of sardine herrings each year in the Inspectors' divisions of Charlotte and Saint John counties. It was thought, however, that useful information could be gathered if some statistics were arranged in much more detail. Owing to the courtesy of Messrs. Connors Bros. and the R. J. Peacock Canning Co., we were enabled to collect special statistics giving the amount of detail desired. The two firms chosen operated on a large scale and the locations are favourable, one on the eastern side of the Passamaquoddy entrance and the other on the western side.

We include the years 1927, 1929 and 1932. For 1927 and 1929 our statistical unit is one "weekly purchase" of sardines from a fisherman. For example, an entry of "6" might mean that six fishermen sold sardines to the firm in one week or that one fisherman sold sardines to the firm in six different weeks. For 1932 we use a different measure, namely a "daily offer" of sardines, so that an entry of "6" would mean either that six fishermen offered or sold sardines to the firm on one day or that one fisherman offered them to the firm on six days. The statistics have been arranged by weeks and by the areas already described in connection with the length measurement work, Section III. The labour of tabulation, which has been considerable, would have been multiplied many times if we had taken into account quantities of sardines in each offer or purchase. For our purpose it has been sufficient to consider all weekly purchases and daily offers as equivalent to all other weekly purchases and daily offers, respectively. Annual summations of these statistics are shown graphically in figure 7. The outstanding feature of figure 7 is that the coasts on the two sides of Letite passage are the most productive in the region, in all three years. The neighbourhood of St. Andrews and the Bocabec-Digdeguash region appear also to be fairly fruitful in all three years. Differences between years are to be
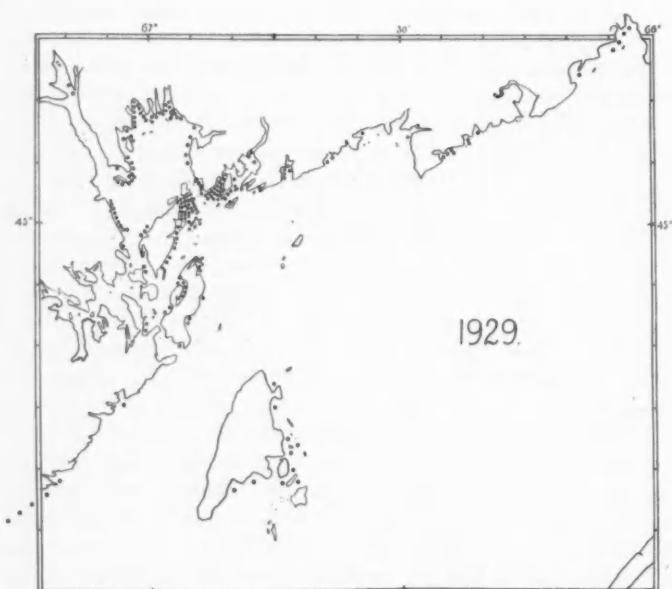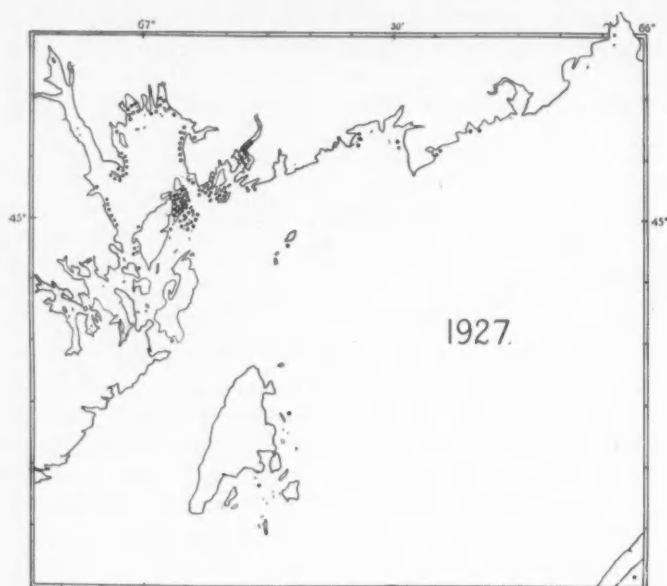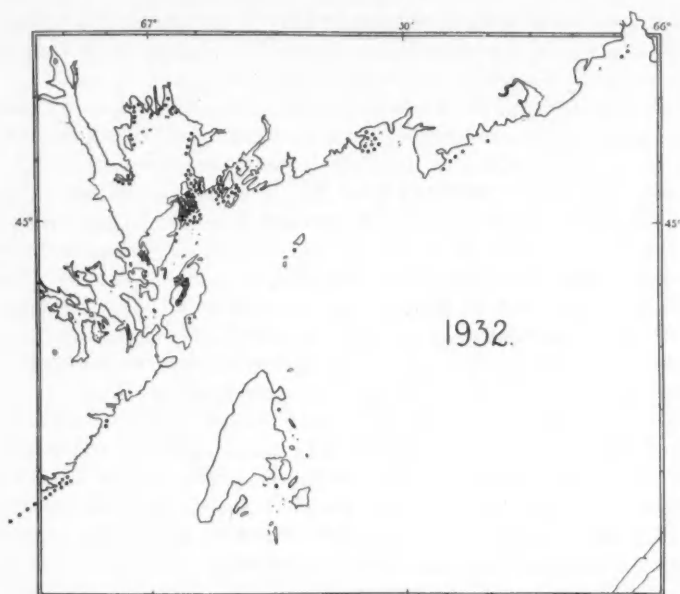
108

FIGURE 7 (part)

FIGURE 7 (con.).   Distribution of sardine purchases or offers.   These charts are prepared from information kindly supplied by Messrs. Connors Bros. and the R. J. Peacock Canning Co. Each dot represents so many lots of herring.   In 1927 and 1929 (see opposite page), one dot represents 10 "weekly purchases" (equivalent in number to weekly accounts settled) by the two firms (acting separately).   In 1932 one dot represents 2 offers of herring to the two firms (again acting separately).   In all three years the areas near the Letite passage were clearly the most productive (see also figure 16).   The years also show peculiarities, which are discussed in the text, p. 109.

noted in the richness of Pocologan and Harbour de Loutre in 1932, as compared with their comparative poverty in the other two years.   Another difference is the remarkable yield from the L'Etang river in 1927, which was not repeated in 1929, nor 1932.

Bias in these statistics is, so far as I could discover, only applicable in two respects.   Firstly, Connors Bros. own the company operating most of the weirs on Frye's island which abuts on the eastern side of the rich Letite area, and in 1929 the Sea Coast Canning Co., whose records we are using, acquired weirs in the Machias district, which would bias their purchases in that direction.

The weekly charts of these statistics show many points of general interest, but not sufficiently relevant to warrant their presentation in full.   Information from which they can be drawn is on file with the Biological Board of Canada. We have already seen that the length measurements suggest immigration of extensive bodies of young herring (taken in weirs over a wide area) and these data of purchases are not incompatible with the same theory, although they do not show it so clearly.   For example, in table IX an extract has been made of

the weekly purchases in Passamaquoddy bay areas and Grand Manan areas, and there is sufficient correspondence between the *changes* in the two series of figures to suggest frequent supply from the same source.

The unpublished charts revealed interesting cases of one locality maintaining a supply for a long time, in all three years. In 1927, the L'Etang river supplied sardines from the beginning of July to the end of October, without a single blank week, whereas in 1929 and 1932 this area (11), provided few sardines. In 1929, Dipper harbour (area 5), sold sardines in fifteen weeks out of sixteen between June 15 and October 12, and in eight of those weeks neighbouring areas did not sell to these factories. This phenomenon is ascribed by the fishermen to the herring being penned into bays by their enemies. In 1932 it occurred in Pocologan, where the herring were taken in the middle of July and continued to be taken until the 24th September. Special efforts were made to find whether a remarkable food supply was holding the herring in Maces bay, but plankton hauls taken with the metre net (XXOOOO-XXO) at stations M 1-M 12 revealed nothing abundant, except moderately young eggs of Euphausiids. The fishermen concerned assured us that the herring were not particularly full of food. They were described as "clear of feed". Inquiries by Captain Mitchell of the "Phalarope" in Beaver harbour revealed that the line fishermen of that port had been taking a fair quantity of hake and haddock on the grounds between Beaver harbour and point Lepreau, but that they had had to abandon this fishery owing to an invasion of dogfish in late July. An explanation of the Pocologan herring fishery might, therefore, be that an extensive school of dogfish was holding the herring into Maces bay. The silver hake, *Merlucius*, is more usually credited with the agency for this phenomenon.

Looking over the weekly charts an impression is gained that the first sardines to be taken in the spring are from a not very large population, which has remained during the winter in the region between point Lepreau and Deer island. In 1927 it looks as if this body, whether reinforced or not, entered Passamaquoddy bay only at the beginning of July, whereas in 1929 they were already in the bay in the week ending April 27. The impression is further gained that this winter school is joined by more sardines from the open sea earlier or later in the season, which eventually leave the Quoddy region, so that, at the end, only the passages of Passamaquoddy bay are fishing, just as they were at the beginning of the season. However, no great reliance is to be placed on this impression, which needs substantiation by further research.

V. HERRING FRY INVESTIGATIONS

Figure 8 shows charts of our observations on herring fry (excluding the June cruise, when hardly any were taken). Details are given in tables on file with the Biological Board of Canada.

In September 1932 we took a fair quantity of herring fry from the bay of Fundy, principally on the Nova Scotian side. These were mainly 10 to 11 mm. long; smaller fry were taken southwest of Grand Manan and larger fry near Saint John. None was taken near Petit Manan nor in the vicinity of the Lurcher shoal. It is clear that the fry taken were mainly the product of fairly local

spawning in July or August. From the catches of large breeding herring, it is known that there is a considerable spawning ground south west of Grand Manan. By repute, Grand Manan bank is also a spawning ground and there are probably others in places where there is no fishery for the adult herring. The June cruise and the September cruise make it clear that spring spawning produces no considerable contribution to the herring stock, for we took no freshly hatched fry in June, nor any outstandingly large fry in September. This is confirmed in the records of herring fry taken in the zooplankton cruises, of which Dr. Fish has sent me an extract.

Our catches of fry on the Nova Scotian shore in the previous December and January, mainly 22 to 26 mm. long, can be related to the corresponding spawning of the year before. We also sampled in January an extensive body of fry off cape Sable, and similar but even more extensive distribution was found in April. From January to May, the bay of Fundy contained a moderately extensive body of fry on the Nova Scotian side. The Quoddy area and the coast of Maine, notable for the large landings of sardines, were not found to be well supplied with fry at this helpless stage. A remarkable feature of these observations is the general scarcity of herring fry in the bay of Fundy and neighbouring waters. It is true that the method of fishing was probably inadequate from May onwards, (owing to the fry becoming large and therefore active enough to avoid the net), but the fry were found to be scarce in January also. At no time did we find any population of fry commensurate with the enormous numbers of sardines, unless the body taken in April between Seal island and Liverpool is considered sufficiently extensive. The observations, in fact, suggest that neither the Grand Manan spawning ground, nor all the spawning grounds in the bay of Fundy considered together, provide sufficient fry for the population of sardines. If this be true, then the Quoddy-Maine sardine fishery must represent concentration in a small area of the products of very widely distributed spawning grounds.

Growth was apparently very slow from February to April. Within the bay of Fundy the distribution of herring fry would make it appear that there is very little water movement from February to April while the Saint John and other rivers are frozen, and this is supported by the distribution of plankton (Chaetognatha and Ctenophora) (see section VIII), but neither of these lines of evidence can be relied on more than as an indication for further research.

VI. FIRST APPEARANCE OF METAMORPHOSED HERRING

Very small herring, sometimes called "eyeballs", are sometimes seen by fishermen round the coast. It appeared to us from consideration of the work of Mavor (1922, 1923) and of Bigelow (1927), that the currents would set the herring fry, observed in April near Seal island, on to the coast of St. Mary bay in July. With this idea, Mr. James Bates visited Brier island on July 10 where he was fortunate enough to find that the pollack had driven a large quantity of herring of about 5 cm. length on to the beach. At the same time similar herring were taken in the Biological Station's weir at St. Andrews, and report gave them a fairly wide distribution in Passamaquoddy bay. Mr. N. A. McNairn has given

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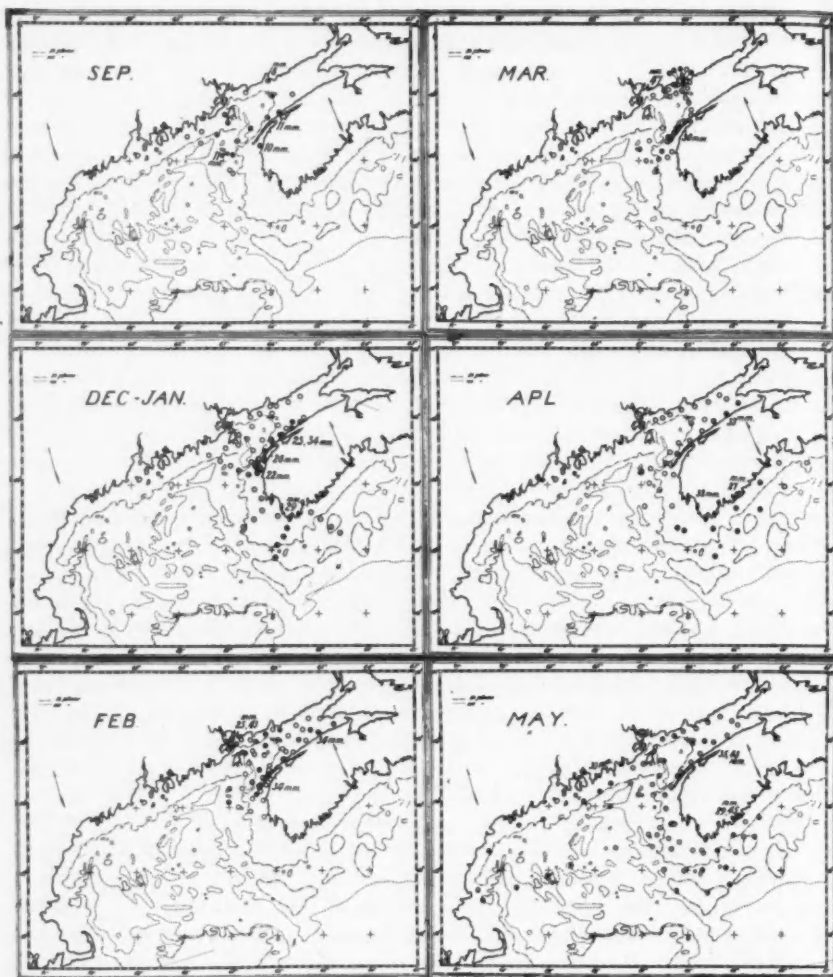
FIGURE 8. Catches of herring fry. In this series of charts positive hauls are shown solid, negative in outline. "Peak" or most common lengths are inscribed near the hauls to which they refer. The numbers per haul were always relatively small (Data on file). It is suggested in the text, p. 111, that the Dec.-Jan. chart shows a distribution derivable from that of the September chart (although the September chart was for the following year), and that the bay of Fundy stock is thus adequately sampled by the observations up to, say, April, showing it as a disperse, and nowhere very numerous, population. Allowing that the fry are more difficult to catch in April and May, owing to their larger size and activity, and that mortality will have thinned them, the stock in April (and May) lying to the south of Nova Scotia is clearly more extensive and abundant.

The sardine area (cf. figure 1) was poorly supplied with herring fry at this (passively drifting) stage.

me an extract of his records of the catches in this weir. These show herring mainly of 6-7 mm. length on July 9 and 13, say 4, 5, 6 and 7 mm. on July 14 and 16, and 8-9 mm. at the end of July and on August 16. The fishermen were unanimous that these would become suitable for canning in about October. We might mention here that in 1931 we saw a barrel of very small sardine herring which had been taken at Shelburne.

The appearance of a later stage, the youngest marketable fish, 10 cm. length in September, has already been noted, section III.

A point of some interest is whether the extensive body of fry that we found in April (figure 8), apparently extending from Seal island round cape Sable to the offing of Liverpool, would tend to be carried to the sardine area. Some limited experiments with drift bottles suggest that they would. Of 50 bottles liberated on a line across La Have bank on July 16, only two (nos. 481, 499) were recovered by March 1933. These two were liberated on La Have bank. One was found at Port Latour on the south shore of Nova Scotia in October, the other near Parkers cove on the Nova Scotian shore of the bay of Fundy in December. Messrs. Herrington and Webster of the U.S. Bureau of Fisheries have kindly supplied particulars of recoveries of bottles liberated between Georges bank and cape Sable. Two liberated near cape Sable in May, Station N 243, were recovered in July and August in the sardine area in the Maces bay neighbourhood. 16 other bottles, liberated in April, 1932, on Browns bank, the neighbouring part of Georges bank and the channel between, were recovered as follows: 1, Newfoundland; 2, outer Nova Scotia; 3, between cape Sable and St. Mary bay; 1, Nova Scotian shore of bay of Fundy; 1, Chignecto side of head of bay of Fundy; 1, Grand Manan; 6, between point Lepreau and West Quoddy head; 1, near Gt. Wass island, which is about midway between Passamaquoddy bay and Mt. Desert island. All but two of the recoveries were made before September 30, 1932.

It seems probable that some, at any rate, of the fry we found in April extending around cape Sable would tend to be drifted into the bay of Fundy, although they might well have passed the "eyeball" stage before reaching the sardine area proper. Of course, should the herring choose to resist the drift, which they would be capable of doing at this stage, this tendency might be nullified.

VII. STUDY OF PHYSICAL CONDITIONS

This branch of the investigation was the concern of my colleagues rather than myself. A special effort was, however, made to compare the coastal waters of Nova Scotia with those of Maine and Fundy in regard to surface temperature and transparency. The observations are given in table I. It was found that in July the most turbid water (between Portland, Maine, and Liverpool, Nova Scotia) was in Passamaquoddy bay and off the Saint John river. The central part of the bay of Fundy, the mouth of St. Mary bay and the water near cape Sable was relatively clear. The whole coastal water between cape Spencer and Seguin, which is approximately the sardine area, was more turbid than anywhere else except the inner part of St. Mary bay and the Annapolis basin, where

sardines are also taken. The corresponding surface temperature observations showed the coldest water off cape Sable and the warmest water in St. Mary bay. The water between cape Spencer and Seguin was intermediate in temperature, warmer west of Mount Desert.

Attention should be called to two factors whose distribution is already known. The bay of Fundy is notable for the extreme range of the tides (figure 9). A range of 45 ft. (13.7m.) is recorded in the Minas basin. Going from St. John to Boston there is a gradual reduction in the range recorded, from 22 ft. (6.7 m.) to 10 (3 m.). The range at Digby is 22 ft. (6.7 m.) at Brier island and Yarmouth 14 ft. (4.3 m.), but around cape Sable, we have only 5 ft. (1.5 m.), at Shelburne and 5 ft. at Halifax. The bay of Fundy is also noted for summer fog. If we examine the records of fog at light stations in July, we find indeed, a large area stretching from Cap d'Or to Petit Manan and round Nova Scotia to Halifax where the fog is extreme (figure 9). In July 1930-31 more than 300 hours per month was recorded in the area described. This is the extreme degree of a general condition which stretches as far west as say, Block island, although with marked reductions in western Maine. Winds from SE. to SW. are known to bring fog, and the condition appears to be due to warm, damp air from the Gulf Stream being driven into a region where the surface water is relatively cold. Figures kindly supplied by the courtesy of the two departments of Marine and Fisheries are given in table X.

The residual current picture plotted by Bigelow, 1927, p. 973, as typical for the month of August, shows that usually, the mouth, at any rate, of the bay of Fundy is part of the gulf of Maine circulation, with some contribution from the waters between cape Sable and Browns bank (figure 10). I understand that our own observations with drift bottles and those of the Biological Board of Canada, for which I am indebted to Mr. H. B. Hachey, agree in showing considerable contribution of water from the gulf of Maine to the mouth of the bay of Fundy. This is the summer condition, and we do not know whether it also obtains when the rivers are frozen.

The question of the bay of Fundy receiving contributions from the cape Sable region was specially discussed in section VI.

Important effects of the conditions mentioned in this section are discussed in the paper by my colleagues Dr. Gran and Mr. Braarud (1935).

VIII. PLANKTON. HERRING FOOD

This side of the work was the chief concern of my colleagues, but in the hauls for herring fry we naturally took other forms, constituting a large collection. The customary handling of these in the laboratory could not be undertaken by my colleagues, whose time was more than occupied in dealing with their own collections. Moreover, the comparatively large mesh used for taking herring fry (Petersen net), was highly selective as regards important herring food such as *Calanus*. The collections, have therefore, been handled by a rapid, approximate, but adequate, method of estimation, and the distribution of the commoner groups of animals has been examined. The distribution of

ctenophores, figure 11, and *Sagitta*, figure 12, in the bay of Fundy, are interesting, as suggesting almost no water circulation at the time when the herring fry were taken. It is observed that the ctenophores were consistently located principally between cape St. Mary and Digby, and the greater concentration of *Sagitta* was consistently near Digby. Absence of water circulation is the readiest explanation, but it does not follow that this is the true one. The truth may be
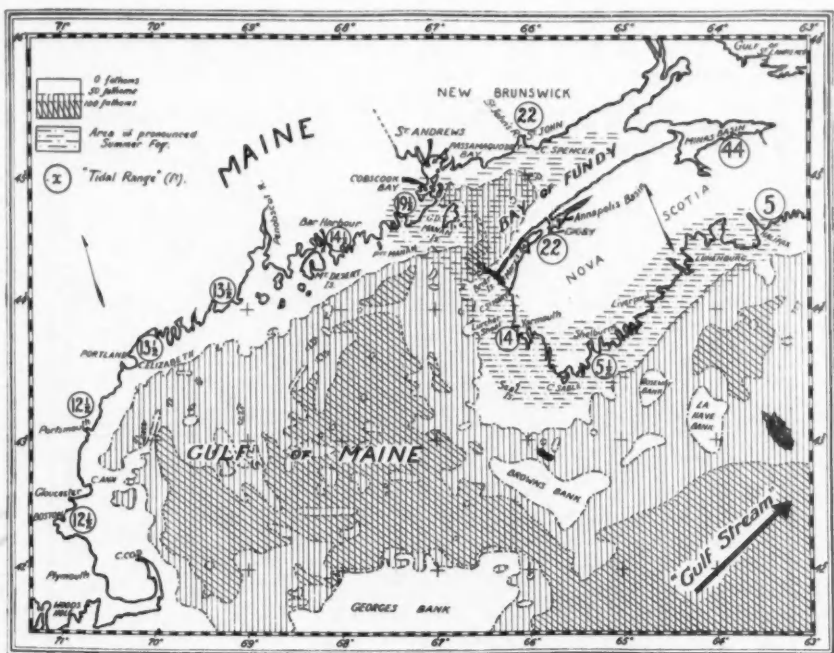
FIGURE 9. Topographical chart of area of investigation. This chart shows depths and place names, also "Tidal Range" and fog. For the Canadian coast the "Tidal Range" is 2 (H. W. Springs level—Mean level) whereas for the U.S. coast we have used a value which comes 2 to 3 feet more namely (H. W. height—Lowest tide). These figures were taken from the respective charts. Fog figures are given in table X. The shaded area includes stations where there was 300 hours or more of fog in July, on the average of years 1930, 1931.

Fog is an indication of cold surface water. The tidal range falls, as one leaves the sardine area, going westward and southward.

more complicated, for example, the localities of abundance may be unique in the conditions for survival of the forms, or as points of concentration by mechanical forces, and other explanations may, no doubt, be suggested. The distribution of euphasiids near Saint John in March is shown in figure 13. This is submitted to show the irregularity of euphausiid catches, even with a large net fished from very near the bottom to the surface. The matter is important because these "shrimps" are one of the favourite foods of the sardine herring, and their appear-

ance on the surface is a very frequent phenomenon in the Quoddy area. This appearance on the surface seems to be related to upwelling of deep water, for it is associated with tide streaks. The appearance of the "shrimp", which are easily seen, is generally heralded by concentration and excitement of herring gulls, terns and phalaropes. On occasion, herring may be seen darting about under the places where the shrimp are. Such were the phenomena observed off Welchpool (area 22, figure 5), one day in the summer of 1932. On that day the herring were not observed under the "shrimp" until sunset. The distribution of one of the principal tide streaks, as we normally observed it, and of the gulls as observed one day when a census was taken, are shown in figure 14.
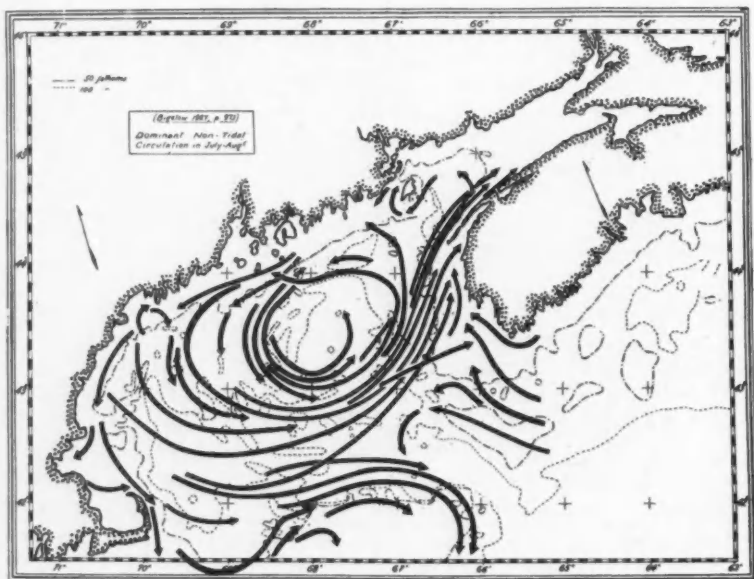
FIGURE 10. August circulation of surface water according to Bigelow. The author of this chart explains that it is made from drift bottle records and is to be regarded only as typical of the circulation shown, not necessarily applying every year.

Figure 15 is a snapshot of about one quarter of one of these gull concentrations. In the short cruise of the "Phalarope" on the 17th and 18th of August 1932, large quantities of euphausiid eggs were taken off Bliss island and in Maces bay, stations M 1 to M 12, with the metre net (XXOOOO-XXO), and local fishermen reported the adults as forming the food of ground fish at that time. It certainly appears that there are large quantities of these "shrimp" in the mouth of the bay of Fundy and elsewhere in the region. (Our records show them commonly off cape Spencer). Undoubtedly euphausiids cannot easily be sampled in a representative manner. A series of 20 hauls were made off Liverpool, Nova Scotia, stations N 217-N 236 with the Petersen net, with the intention of dis-
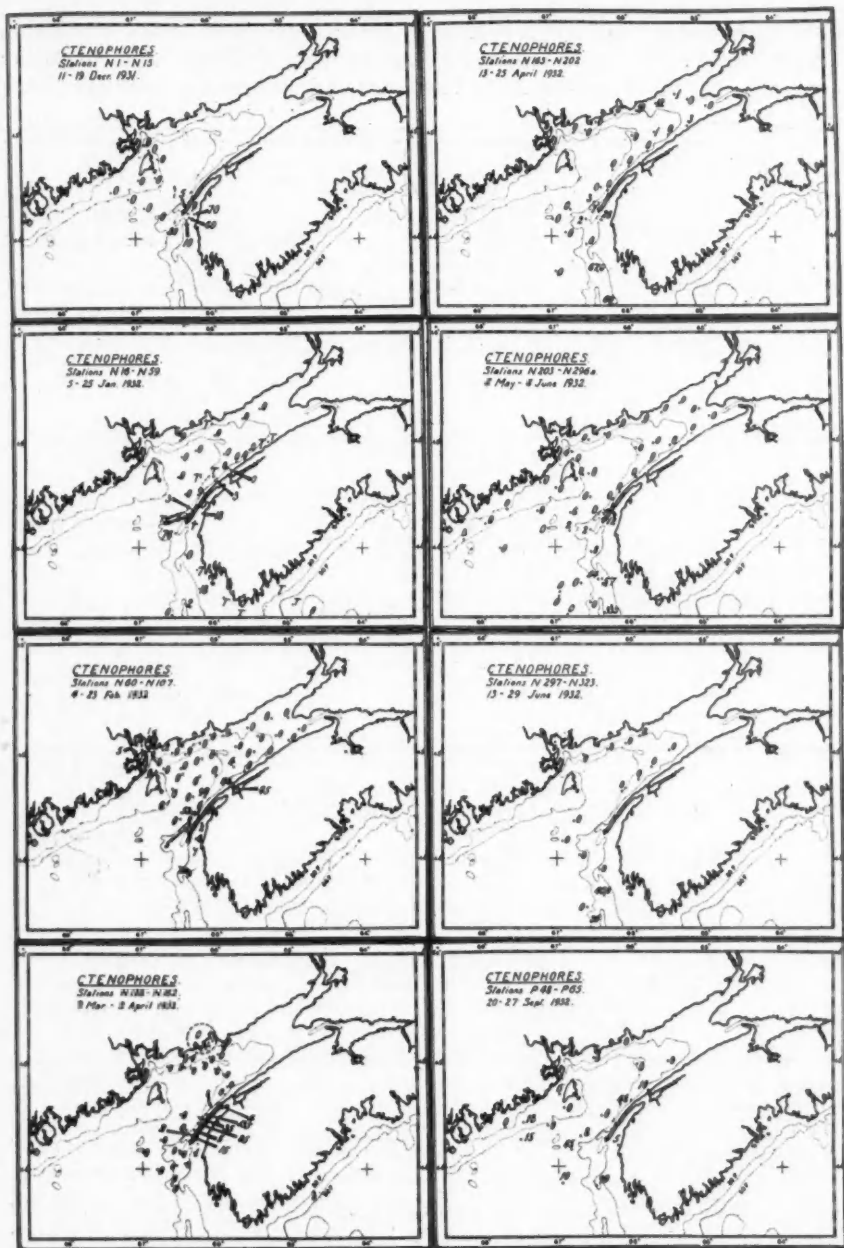
FIGURE 11. Catches of ctenophores. The distribution of these forms is remarkably constant and restricted. They suggest absence of circulation in the bay of Fundy, but can also be interpreted otherwise. The numbers are estimated volumes (in 1/100s of a cylinder, vol. 500 cc.). "T" stands for "trace".

discovering what difference, if any, there was between our day and night catches of herring fry. These hauls did not show any significant difference in the catches of herring fry by day and by night, but it was obvious from the mere appearance
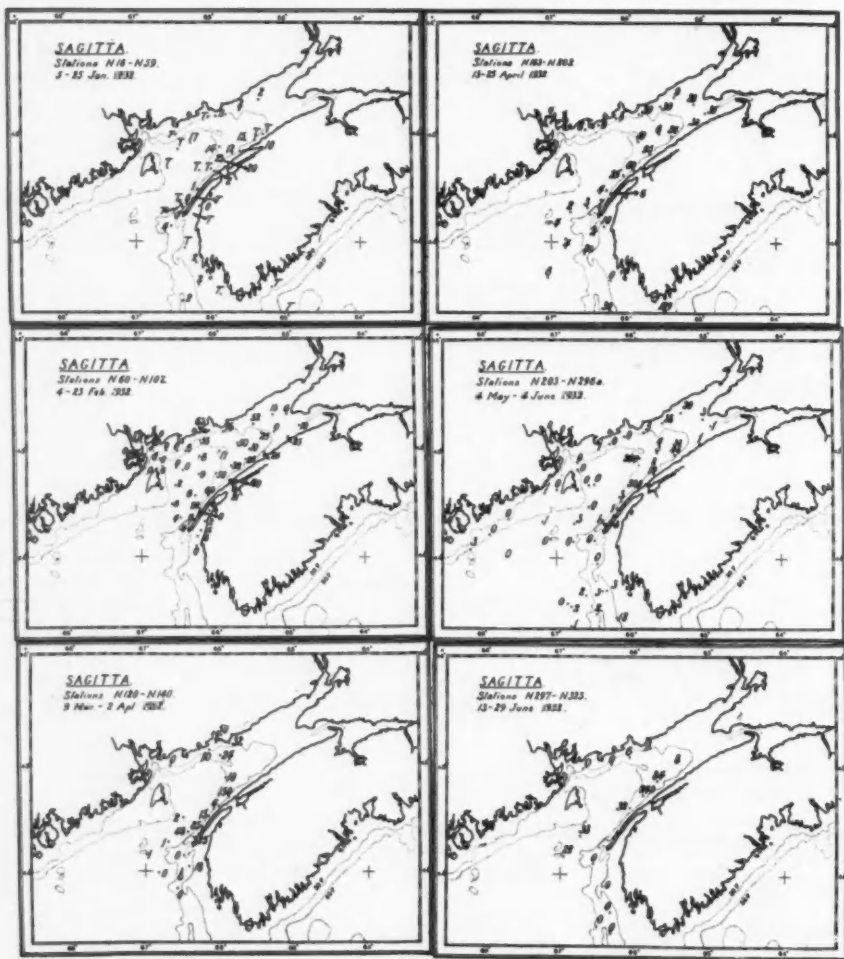
FIGURE 12. Catches of *Sagitta*. The distribution of this form is again remarkably constant (cf. figure 11), suggesting very little circulation in the bay of Fundy, but can also be interpreted otherwise. The numbers are estimated volumes (in 1/100th of a cylinder, vol. 500 cc.).

of the plankton in the jars that they would give information about the liability of euphausiid and other forms to capture. These hauls, therefore seemed worthy of more exact treatment than we had accorded to the remainder of my collection, and have been examined quantitatively by Mr. A. C. Gardiner, temporarily

working at the Fisheries Laboratory, Lowestoft. His report appears to be of considerable interest from the point of view of other food animals, such as the copepods, as well as in regard to the euphausiids. It is as follows:

SUMMARY REPORT ON 48-HOUR PLANKTON COLLECTION

By A. C. Gardiner

The collections, twenty in number, were obtained by oblique hauls, from bottom to surface, of a modified 2 metre ring-trawl (Petersen net).

The twenty hauls were made at approximately 2½ hour intervals and covered a period of 48 consecutive hours; 10 were made during the hours of darkness and 10 in daylight.
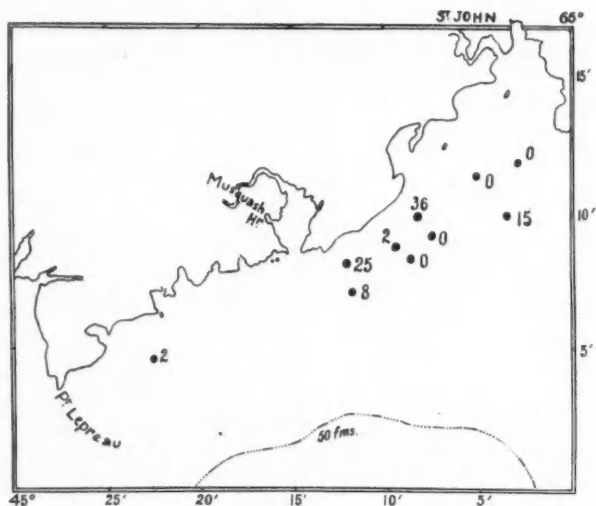
FIGURE 13. Catches of euphausiids near Saint John. This chart is included to show the extreme "spottiness" of catches of euphausiids in hauls close in time and distance (Stas. N 121-125 and N 141-153). Numbers indicate estimated volumes, as in figures 11 and 12.

There were considerable differences between daylight and dark collections. The most striking was in the case of euphausiids (*Thysanoëssa inermis*, *Thysanoëssa raschii* and, very few, *Thysanoëssa longicaudata*), the numbers of which rose to over 5,000 by midnight, whilst in all the daylight collections the animals were virtually absent (0-40 per haul).

As regards the other common species, *Sagitta elegans*, *Calanus finmarchicus* and *Calanus hyperboreus*, it was shown that there was a significant difference between the numbers captured in the daylight and dark collections, the latter being in each case the greater. Adult *C. finmarchicus* tended to disappear to a relatively greater extent than individuals in stage V.

Numerical differences between day and night collections have been noted before but the present data, especially those of euphausiids and *Sagitta*, covering as they do a period of 48 consecutive hours, are particularly interesting.

It is well known that euphausiids, which are believed normally to live in the deeper water by day, may on occasions be found in great abundance right at the surface at midday. This phenomenon was observed during the course of the present experiment, "shrimp" being observed from the deck of the ship in fair numbers round about midday on the second day.

A single specimen captured in a surface bucket was identified as *Th. inermis*. The number of all species of euphausiids taken in the oblique haul at the time nearest to that when "shrimp" were being observed in the surface waters was 29, the maximum number in the preceding period of darkness being 4,179.

Two explanations suggest themselves. Either we believe that these animals being powerful swimmers, can see and avoid a net by day, or we can suggest that normally these animals are
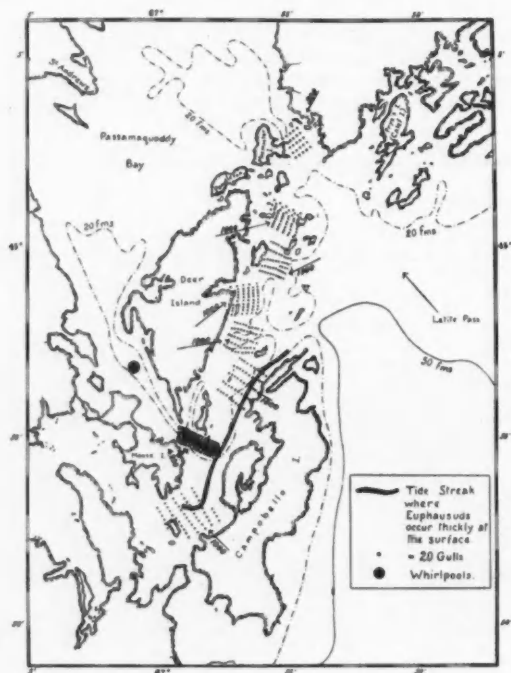
FIGURE 14. Whirlpools, gulls and tide streaks in Passamaquoddy entrances. This chart is largely schematic, for illustration, rather than record. The whirlpools are taken from the admiralty chart. The position of the main tide streak is from memory of several occasions. The gull census is the result of observations on one particular tide, when two patches were photographed and the remainder of the population estimated in terms of these two patches. Subsequently the numbers in the patches were counted on enlargements, and so the whole census evaluated. The total number came to 11,000. We only saw the waters of the main entrance, Friar roads, the way to Letite passage and Letite passage itself, with two traverses of Passamaquoddy bay.

nocturnal, a period of inactivity by day following the period of activity during the hours of darkness. When, for some reason, the animals' normal rhythm is upset a number may swim up to the surface in the daylight where the net fails to catch more than a small proportion due either to the animals' own efforts to dodge the net, or to their being on the quite superficial water layers through which an obliquely hauled net would not normally pass.

The suggestion will be made that the big differences observed between the numbers of euphausiids, *Sagitta* and *Calanus* spp. by day and night probably lies in the fact that to a greater or less

degree these animals are nocturnal. In the day time a proportion (close on 100% in the case of the euphausiid species) sink right to the bottom and are removed from the population sampled by the net. In the case of the other species the proportion which are so removed is smaller.

Neither fish ova or herring larvae show significant differences between daylight and dark collections.

Mr. Gardiner has briefly described these results elsewhere (1934).

The whole collection of plankton (excluding the 48-hour hauls dealt with by Mr. Gardiner) has been stored at the St. Andrews laboratory where, presumably, it is available for any interested persons; and the rough charts of dis-

FIGURE 15. Gulls in the Quoddy tide streak. This is a snapshot of about one quarter of a patch of gulls seen off Eastport. (Not on the same day as the census of figure 14).

tribution, which we have prepared, have been sent to Dr. C. J. Fish in case they are of interest in connection with his branch of the investigation.

Considerable quantities of fish eggs were taken on these cruises. It was believed that they might throw light on the currents in the bay of Fundy. Mr. R. A. Mackenzie of the staff of the Biological Board, accepted the task of working out this collection for the sake of the information it should provide about the production and distribution of important fishes, such as the cod and haddock. He has kindly sent me a copy of his counts. We are not concerned here with any significance in the study of cod and haddock. As indicators of drift, it is perhaps just worth putting on record that charts for total count in March, April and May provide neither refutation nor confirmation of the suggestion made in the first paragraph of this section, that there may be little circulation in the bay of Fundy at this season.

IX. DISCUSSION OF THE CAUSE OF LOCATION OF THE SARDINE FISHERY

The view has been held that the effect of the proposed dams on the sardine fishery cannot safely be foretold, until the cause has been convincingly established of the remarkable concentration of landings between cape Spencer and cape Elizabeth. The short investigation which we have been able to carry out, has not, in our opinion, established any factor or factors as the cause of this phenomenon, but it is thought that the investigations have added substantially to the revelant knowledge on which our judgment must be based.

There seems little doubt that the availability of herring for such a long season in the gulf of Maine and the bay of Fundy generally has to do with comparatively equable temperature of the water (exemplified by the resulting fog conditions described in section VII). But when the question becomes more particular and we seek for cause of the concentration of landings between cape Spencer and cape Elizabeth, it is much more difficult. Investigation of the conditions which might affect the distribution and survival of the herring has been the concern of my colleagues. Their reports do not show any simple correlation between the factors studied and the location of the sardine fishery. Many fertile suggestions have, however, been made, principally by Dr. A. G. Huntsman, who was good enough to send me an extremely interesting summary of his views, reached as a result of extensive inquiry and investigation.

Before discussing the causes of the concentration of landings the matter of availability for capture should be considered. There is no doubt that a sardine fishery needs canneries and that canneries need a regular supply of sardine herring. In places, therefore, where the occurrence of sardines is only sporadic we must not expect to find any considerable fishery for them. Sardines cannot be transported long distances to a cannery. They must arrive fresh and must have a comparatively undisturbed passage in the hold of the carrying vessel. In St. Mary bay there is no cannery, but sardine herring occur from time to time. In the summer, when the carrying vessels can rely on a smooth passage of the bay of Fundy, considerable quantities may be transported to the canneries on the New Brunswick side. Mr. A. Wentzell of St. Mary bay very kindly gave me an extract from his records of sales in 1928, when he sold no less than 567 hogshead in rather less than a month. (1 hogshead is roughly equivalent to 1,000 lbs.). It appears, however, that the supply has not attracted a factory to St. Mary bay. In the same way the sardine herring are reported by fishermen on the coast of Nova Scotia generally, and occasionally at the head of the bay of Fundy. But there is no special fishery for them, presumably because the supply is insufficient or irregular. The question of whether there are actually more sardine herring in the sea on the strip of coast between cape Spencer and cape Elizabeth than in other parts of the Gulf of Maine, the bay of Fundy or Nova Scotian waters, is open to argument. There is, however, no doubt at all that the mouth of the bay of Fundy, and (in a decreasing degree as we go westwards), the coast of Maine, provide exceptionally good conditions for the *capture* of sardines in weirs. In section IV, figure 7, we saw the particularly rich fishing of areas 13 and 15 near Letite passage, and we now submit additional evidence

of this. In figure 16 are shown the weirs with the best reputation, according to the Inspectors of Fisheries in Charlotte county. Three inspectors concerned agreed in placing most of their best weirs in the Letite region, which is remarkable for the combination of very strong tides with highly irregular coast line
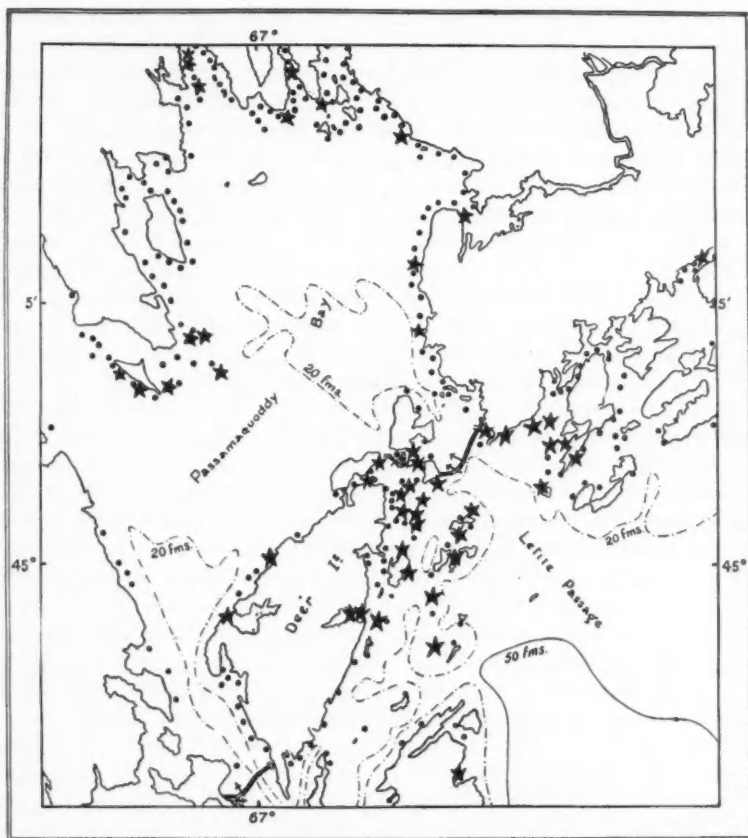
FIGURE 16. Location of best weirs. Sardine weirs operated in recent years are shown as black dots. Those of best reputation are shown with stars. Three Inspectors of Fisheries gave this information, for districts meeting in Letite passage and it is remarkable how the stars are close to that passage, demonstrating its preponderant richness. (See also figure 7). This is close to the main tide and deep water, and the coast is highly indented and irregular.

and many shoals and islands. Examining the chart of figure 9 we see that nowhere in the whole area is there so strong a tide combined with such an irregular coastline, except to the south west of Grand Manan, where also there are many good weirs. The coast of Maine, as far west as cape Elizabeth, is highly indented, but the tides become less strong. It seems from these considerations

that the coast itself may act as a natural trap for herring, and the trap will naturally act more efficiently where there is more interchange of water. Also, more obviously, weir men need sheltered water, provided by the irregular coast line; and the weirs will be more efficient the greater the tides.

We may, therefore, probably discount a proportion of the inequality in the statistical picture, figure 1 (comparing the coast of Maine with the south shore of Nova Scotia), on the grounds of the superiority of the Quoddy-Maine area for catching these sardines. In the present state of our knowledge it would be a brave man who would declare what the proportion of discount should be. It is also uncertain what proportion of the herring population do approach close enough to the shore to be taken in weirs and seines. Dr. Huntsman has suggested (in the manuscript already referred to) that the rise of the sardine fishery was responsible for the dying out of some fisheries for larger herring, by reduction of the stock. Clearly, he seems to think of the sardine fishery as taking a large proportion of the total stock. This matter is, however, open to argument. It is difficult to see why the herring of the gulf of Maine should seek the coast (except at spawning time when they must have clean bottom at no very great depth). Dr. Fish's investigations, including some specially made for this purpose, do not show any particular richness of food in the coastal waters, as compared with outside. Turbidity might, however, make the coast more favourable than the open sea (section VII). We have seen that the water in the sardine area is rather turbid, offering sanctuary to the much pursued herring. On the other hand the herring near the coast is in danger of stranding, or being driven ashore by its enemies, and is in the zone of abundance of the bottom-living gadoid fishes, which are not common in the upper waters of the open sea.

It may be important, that in the sardine area and especially in the Quoddy district, the surface water has been found by my colleague, Dr. Watson, to resemble the middle water of the open bay of Fundy, and it may be a considerable factor in their capture that herring carried to the coast would receive little warning of the nearness of the shore from any temperature gradient. (Against this it must also be admitted that the herring taken in the Quoddy region do not show any particular success if they do, in fact, desire to leave the neighbour-hood of the coast after they strike it. This is seen, for example, in the Frye's island catches charted in figure 4, and is specially discussed in section IV).

We may refer to one general deduction that can be made from our own investigations. Firstly, it has already been explained in section V that the fry investigations revealed no concentrated body of very young herring in the mouth of the bay of Fundy, which could be considered as the younger stage of the vast concentration of sardines. Nor did we, immediately after the spawning season, find any significantly greater body of fry from the Grand Manan and other local spawning grounds than we had already sampled during the preceding winter. This suggests that, if there be indeed a concentration of sardine herring, this is a concentration at about the age at which they are caught, of herring from a very wide area. Secondly, the same indication is given by the investiga-tions of length and of cannery purchases, sections III and IV. The fishery, there-fore, is not to be ascribed to local production nor to concentration in the passive

stage. So we have to seek either (*a*) such conditions as would attract herring, considered as active migrants, to the area, or (*b*) mechanical forces directed towards the area, which may carry the herring passively, combined with conditions in the area such that they do not repel the herring. The gist of Dr. Huntsman's conclusions is that the Quoddy area is favourable for sardines because the movements of the water bring both sardines and their food to the area, without removing them to the same extent. This is not the place for discussion of Dr. Huntsman's theory, and the hydrological and planktological considerations involved are rather the concern of my colleagues than mine. But we should note that if Dr. Huntsman's theory be correct, the placing of dams in the area, where a great mixing now takes place, would tend to produce the double effect of reducing the concentration of sardines in the area and of reducing the supply of food. However, according to a preliminary typescript summary of Dr. Watson's investigations, the effect foreseen by Dr. Huntsman is at any rate not expected to be of great magnitude. Neither effect would be expected seriously to reduce the total survival of herring in the sea. A further effect, of reducing the total amount of phosphates and nitrates made available for plant growth, is considered by my colleagues, Dr. Gran and Mr. Braarud, who do not anticipate any noticeable effect outside the Quoddy region.

X. SUMMARY. EFFECT OF THE PROPOSED DAMS

1. From September 1931 to November 1932 observations were made in the area of the sardine fishery and the sea between Boston and Liverpool, Nova Scotia. The information collected, and published statistics, were studied during the winter of 1932-1933 (section I).

2. The fishery for sardine herring (caught in weirs) is described, and shown to be partly dependent on extremely local conditions and affected by factors of which we are ignorant. Very productive and very poor weirs may be close to one another and spring and fall weirs may be within a mile of each other in the same bay (section II). (Between cape Spencer and cape Elizabeth is called the "Sardine Area").

3. Study of length measurements of sardines shows that herring first appear in the catches at about 12 months old, in August, and grow until October. Certain areas tend to have larger or smaller sardine herring. Sardine herring are generally segregated into shoals of similar length (within an age-group). Study of the occurrence of particular shoals (as characterised by length) indicates supply to weirs of herring from an extensive body in the more open sea (section III).

4. Study of special statistics of cannery purchases emphasizes the richness of the neighbourhood of Letite passage. Sporadic productivity in restricted localities is shown, and attributed to penning of the herring by enemies, such as silver hake (*Merlucius*) and dogfish. An impression of the stability of a limited part of the stock and a mass migration of the remainder is suggested by these statistics, but, no great reliance is placed upon this, for the statistics may well

be readable some other way; this impression is, however, consonant with the findings of section III, above (section IV).

5. Special investigation of the stage when herring fry are small, and presumably passive drifters in the sea, revealed no special supply to the sardine area. On the contrary , the bay of Fundy was poorly supplied (although probably containing the total product of its own spawning grounds); whereas an extensive body of fry off and around cape Sable would probably be directed to the sardine area at a later stage, when, however, they undoubtedly could swim against the current (sections V and VI).

6. Only turbidity was found to be a possible physical factor which might render the sardine area specially attractive to herring. On the other hand the prevailing circulation of water in the gulf of Maine passes through the sardine area (section VII).

7. Euphausiids at the surface form one of the striking features of the Quoddy region (the heart of the sardine area). Catches show that there are large quantities of these elsewhere in the bay of Fundy, but their capture was irregular. Study (by Mr. A. C. Gardiner) of a collection of plankton made in connection with herring fry catches, results in the conclusion that the principal plankton species then taken (except herring fry and fish ova) behaved in a manner best explained by diurnal quiescence and nocturnal activity. (Forms: *Thysanoessa spp. Calanus spp. Sagitta elegans.*) It seems that the sardine area probably contains adequate food for the herring (section VIII).

8. The disproportion in landings of sardine herring in the sardine area, as compared with the rest of the gulf of Maine, bay of Fundy and Nova Scotian waters (figure 1), is partly to be explained on the grounds of especial ease of capture in the sardine area. But it is uncertain whether there is, nevertheless, a disproportion in the populations in the sea in various areas. Only turbidity has been found in our investigations to be a possible favourable factor in the sardine area, and the coastal region is in other ways obviously unfavourable. Dr. A. G. Huntsman's view is that the movements of water bring both sardine herring and their food to the area, without removing them to the same extent; the effect depending on a strong mixing mechanism and a supply of fresh water (section IX).

9. Truly to foretell the effect of the proposed dams we need more detailed, and more certain, knowledge of the herring, than our brief investigation has supplied. But the above considerations lead to certain conclusions in this matter. It is clear from what we have seen, in paragraph 2, of the extremely local nature of the factors affecting the sardine fishery, that the dams would make considerable havoc of the exceptionally rich fishery in their nighbourhood (paragraph 4). These local effects would be expected to be considerable, although the general tidal effect be comparatively slight. Hachey (1934 b) foresees a definite but slight increase in tidal amplitude. The fishery inside the dams would almost certainly be reduced to negligible proportions, since it seems

dependent on immigration (paragraphs 3-5).* Outside the dams it is not so clear. Considerable changes in the set of the tidal streams may be expected, and, since the fishing of weirs is so locally peculiar (paragraph 2), every little change would be expected to have an effect on the fishery of nearby weirs. Some would be made richer, some poorer. On this basis it cannot be foretold whether the total effect on capture immediately outside the dams would be deleterious or not. But, if Dr. Huntsman is right in relating the Quoddy fishery to tidal mixing (paragraph 8), the effect on the fishery in the Quoddy region would probably be serious; that is, partial interference with the mixing mechanism would reduce the amount of herring and of their food brought to the locality. Even with the dams in place there would, however, be *some* mixing of the bottom and surface waters; and a measure of Dr. Huntsman's effect is not to hand. Going further afield, the apparent independence of the main stock from purely local conditions (paragraphs 3, 4, 5), makes it appear that there is little possibility of a widespread effect, for example, along the coast of Maine, or even seriously at Grand Manan.

*In the Damariscotta river at East Boothbay, Maine, there is a small tidal mill. Herring rarely enter through the sluice gate, according to information collected on the spot. The opening of the gateway is about 12 ft. wide by 10 ft. deep. I am indebted to Captain Greenleaf of the U.S.B.F.V. "Pelican" for calling my attention to this mill and to Mr. T. H. Dorr of the U.S. Fish Hatchery for taking me to see it.

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128

TABLE 1. Temperatures and Secci readings

T_1 = Temperature at surface.

| (Passamaquoddy bay to Digby) | | | | (St. Mary bay to cape Sable)—*cont.* | | | |
| Station | | | | Station | | | |
No.	T_1	Secci	Light on disc	No.	T_1	Secci	Light on disc
P 1	10.9	4.2	shade	P 24	12.3	11.5	sun
P 2	10.1	7.0	shade	P 25	5.8	14.0	sun
P 3	9.6	6.7	sun	P 26	4.0		
P 4	9.9	6.7	sun				
P 5	9.7	4.3	sun and shade	(Cape Sable to Liverpool)			
			(made no difference)	P 27	5.3		
P 6	10.4	4.0	shade	P 28	6.0		
P 7	9.5	4.8	rain	P 29	7.8		
P 8	10.7	12.0	shade	P 30	9.5	8.0	sun
P 9	11.8	12.2	sun	P 31	5.9	7.9	sun
P 10	9.2	7.3		P 32	6.8	8.8	sun
				P 33	7.2	8.9	sun
(Digby to St. Mary bay)							
P 11	8.8	8.7	sun	(Portland to Grand Manan)			
P 12	9.3	9.2	sun	P 34	13.7	9.0	shade
P 13	9.7	8.1		P 35	12.6	5.8	sun
P 14	10.3	8.6	sun	P 36	13.1	7.3	sun
				P 37	12.3	5.6	sun
(St. Mary bay to cape Sable)				P 38	11.7	5.5	sun
P 15	13.8	6.9	sun	P 39	11.0	5.1	sun
P 16	14.9	6.5	sun	P 40	12.5	6.2	sun
P 17	15.2	6.3	sun	P 41	11.1	6.1	sun
P 18	11.5	6.2	sun	P 42	10.3	6.1	
P 19	9.9	8.1	sun	P 43	9.3	5.0	
P 20	11.8	11.6	sun	P 44	9.5	6.3	sun
P 21	10.5	7.1	sun	P 45	8.5	7.1	shade
P 22	10.7	8.6	sun	P 46	9.3	7.1	overcast
P 23	12.4	10.3	sun	P 47	9.0	6.1	overcast

TABLE II. Herring landings in Fundy and Maine

Landings of herring (including Canadian sardines) per unit of coast length
per annum by counties. (Coast measured on a chart 18 nautical
miles to the inch)

County	1919	1928	1929	1930	Average
Lunenburg	22	8	31	23	21
Queens	35	6	29	22	23
Shelburne	11	4	13	16	11
Yarmouth	11	14	16	25	17
Digby	10	23	7	10	13
Annapolis	8	33	28	9	19
Kings	3	2	4	5	4
Hants	..	0	0	0	0
Colchester	..	1	0	0	0
Cumberland	0	0	0	0	0
Westmoreland	4	0	0	0	1
Albert	0	0	..	0	0
St. John	43	180	65	49	84
Charlotte	258	300	341	218	279
Washington	157	117	143	127	136
Hancock	69	22	36	33	40
Waldo	97	55	71	2	57
Knox	88	50	169	81	97
Lincoln	47	64	66	65	61
Sagadahoc	5	8	5	13	8
Cumberland (U.S.A.)	31	99	118	116	91
York	..	..	..	1	0
Rockingham	..	..	..	3	1
Essex	24	24	29	11	22
Suffolk	8	35	134	149	82
Norfolk	..	..	..	3	1
Plymouth	24	6	33	11	19
Barnstaple	36	11	23	15	22

TABLE III. Herring landings in Charlotte and Saint John counties

Average monthly landings of herrings (excluding sardines) in Charlotte county and Saint John county based on Inspectors' monthly returns 1920-31 for Charlotte county and 1928-31 for Saint John county excluding 1923 and 1924 except for western Charlotte, and excluding 1920 and 1922 for western Charlotte. (1,000 lb., 454 kg., lots.)

	Grand Manan	Campobello and W. Isles	Eastern Charlotte	Western Charlotte	Saint John county
January	30	43	56	3	1
February	118	8	35	3	2
March	216	22	37	. . .	3
April	104	139	64	5	nil
May	48	175	38	45	nil
June	56	175	31	22	nil
July	545	436	63	21	nil
August	3766	442	108	18	85
September	6238	629	79	152	221
October	2307	317	45	148	105
November	361	164	8	113	57
December	50	200	6	12	nil

TABLE IV. Sardine landings in Charlotte and Saint John counties

Average monthly landings of sardines in districts of Charlotte county and Saint John county based on Inspectors' monthly returns 1920-31 for Charlotte county, and 1928-31 for Saint John county excluding 1923 and 1924, except for western Charlotte. Hogsheads (roughly equivalent to 1,000 lb., or 454 kg.).

	Grand Manan	Campobello and W. Isles	Eastern Charlotte	Western Charlotte	Saint John County
January	nil	8	3	nil	nil
February	nil	nil	nil	nil	nil
March	nil	nil	56	nil	nil
April	37	360	542	110	nil
May	55	1300	758	923	15
June	201	986	701	654	44
July	374	1280	787	874	314
August	977	2737	1497	1264	2153
September	753	2205	1677	2095	2429
October	2624	895	945	1548	966
November	274	412	357	282	48
December	2	111	7	27	nil

TABLE V. Sales (in tenths of a hogshead, say 100 lb. lots) of herrings from weirs of the Frye's Island Corporation (By courtesy of Messrs. Connors Bros.)

	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Birch Head									
1928..........	Nil	89	Nil	235	1000	1075	152	164	Nil
1929..........	Nil	139	55	49	25	179	42	Nil	Nil
1930..........	36	727	Nil	Nil	133	23	Nil	Nil	Nil
1931..........	192	90	49	Nil	70	35	Nil	Nil	Nil
1932..........	6	114	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Total.......	234	1159	104	284	1228	1312	194	164	Nil
Average.....	47	232	21	57	246	262	39	33	Nil
Bar Weir									
1928..........	Nil	137	91	59	65	Nil	Nil	95	Nil
1929..........	5	345	43	66	242	150	Nil	Nil	Nil
1930..........	83	1505	159	Nil	Nil	Nil	Nil	Nil	Nil
1931..........	420	50	85	581	280	Nil	Nil	Nil	Nil
1932..........	68	364	Nil	Nil	Nil	145	Nil	Nil	Nil
Total.......	576	2401	378	706	587	295	Nil	95	Nil
Average.....	115	480	76	141	117	59	Nil	19	Nil
Fox Island									
1928..........	Nil	574	106	93	165	Nil	55	Nil	Nil
1929..........	26	255	58	168	35	120	Nil	Nil	Nil
1930..........	53	1112	200	Nil	Nil	Nil	Nil	Nil	Nil
1931..........	204	50	125	407	Nil	Nil	Nil	Nil	Nil
1932..........	Nil	378	254	Nil	Nil	178	Nil	Nil	Nil
Total.......	283	2369	743	668	200	298	55	Nil	Nil
Average.....	57	474	149	134	40	60	11	Nil	Nil
Calef Beach									
1928..........	Nil	Nil	Nil	80	835	1820	445	1035	355
1929..........	Nil	Nil	Nil	Nil	683	1054	4	Nil	Nil
1930..........	140	459	288	Nil	120	547	60	Nil	Nil
1931..........	Nil	Nil	Nil	438	1888	540	Nil	Nil	Nil
1932..........	Nil	Nil	Nil	Nil	70	1195	Nil	Nil	Nil
Total.......	140	459	288	518	3596	5156	509	1035	355
Average.....	28	92	58	104	719	1031	102	207	71
Tarpot									
1928..........	Nil	Nil	Nil	15	330	1370	50	279	Nil
1929..........	Nil	Nil	Nil	Nil	Nil	140	Nil	Nil	Nil
1930..........	Nil	Nil	Nil	Nil	38	497	100	Nil	Nil
1931..........	Nil	Nil	Nil	Nil	206	320	Nil	21	Nil
1932..........	Nil	10	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Total.......	Nil	10	Nil	15	574	2327	150	300	Nil
Average.....	Nil	2	Nil	3	115	465	30	60	Nil

TABLE V.—*Continued*

	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Cumberland Shore									
1928.........	Nil	520	97	241	2165	115	570	2121	Nil
1929.........	366	1439	Nil	233	316	1925	89	Nil	Nil
1930.........	2131	1384	110	Nil	370	352	Nil	Nil	Nil
1931.........	1756	787	270	768	537	400	Nil	Nil	Nil
1932.........	80	1008	23	77	306	1676	Nil	Nil	Nil
Total.......	4333	5138	500	1319	3694	4468	659	2121	Nil
Average.....	867	1028	100	264	739	894	132	424	Nil
Eagle Island									
1928.........	Nil	431	Nil	Nil	655	95	Nil	Nil	Nil
1929.........	140	314	45	355	307	655	Nil	Nil	Nil
1930.........	572	369	74	Nil	Nil	Nil	Nil	Nil	Nil
1931.........	461	791	156	375	254	100	Nil	Nil	Nil
1932.........	50	666	12	Nil	Nil	518	Nil	Nil	Nil
Total.......	1223	2571	287	730	1216	1368	Nil	Nil	Nil
Average....	245	514	57	146	243	274	Nil	Nil	Nil
Charlie's Cove									
1928.........	Nil	808	111	166	422	155	Nil	134	44
1929.........	109	1073	Nil	25	47	8	Nil	Nil	Nil
1930.........	568	626	40	Nil	142	298	Nil	Nil	Nil
1931.........	338	459	114	105	210	Nil	Nil	Nil	Nil
1932.........	25	77	38	5	Nil	205	Nil	Nil	Nil
Total.......	1040	3043	303	301	821	666	Nil	134	44
Average.....	208	609	61	60	164	133	Nil	27	9
Mill Cove									
1928.........	Nil	260	72	72	224	740	120	101	42
1929.........	42	601	14	45	182	12	Nil	Nil	Nil
1930.........	489	1170	207	Nil	Nil	154	Nil	Nil	Nil
1931.........	412	461	86	206	169	Nil	Nil	Nil	Nil
1932.........	120	274	117	101	375	772	Nil	Nil	Nil
Total.......	1063	2766	496	424	950	1678	120	101	42
Average.....	213	553	99	85	190	336	24	20	8
Gooseberry Bar									
1928.........	Nil	798	109	Nil	870	337	Nil	180	12
1929.........	57	478	68	301	481	Nil	Nil	Nil	Nil
1930.........	94	1156	233	Nil	Nil	Nil	Nil	Nil	Nil
1931.........	425	355	41	47	Nil	Nil	Nil	Nil	Nil
1932.........	208	160	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Total.......	784	2947	451	348	1351	337	Nil	180	12
Average.....	157	589	90	70	270	67	Nil	36	2

TABLE VI. Example of data on length of sardine herring, and treatment
(Extract for week ending Sept. 17th, 1932)
B. Blacks harbour.   L. Lubec.

Date 1932 Sep.	Observer	Area	Frequency in 1 cm. length-groups																								"Peaks" (cms.)
			6-	7-	8-	9-	10-	11-	12-	13-	14-	15-	16-	17-	18-	19-	20-	21-	22-	23-	24-	25-	26-	27-	28-	29-	
11·	L·	46													4·	11	11·	22	16	26	13·	11	1	2		1·	21, 23·
11	L	16			4·		2·						2	1	9·	26	28	13	12	18	11	5	1	1		1	20, 23·
11	L	46												2	11	15	31·	28	16	11	12	10	1	1			20, 24·
12	B	3·			13·	35·	37·	15·	9		1·		1·	2·	8		3·	1	2·	3·	5	3·					11, 19, 24·
12	B	15				9·	22·	45·	16·	3	9	2	1·		1·												11, 14·
12·	B·	13·									2	5·	1·	9·	20·	28	15·	5·	6	2·	4·	2·					19·
12·	B·	7·										3·	4·	10·	18·	30	11·	11·	4	4·	3·	1·					19·
12·	B·	12·										1·		1·		3	6·	2·	6·	6·	15	25·	1	1	4	*	25, 28
12	B	36												3·	2·	25	32·	8·	8·	6·	3		2				20
13	B·	15·				4·	26·	40·	31·	3·	1	1·				4	2·	2·	1·	3·							11, 19·
13·	B·	12·					8·	13·	20·	24·	24	31·	23·	19·	10·	2	1·	1·		1·							15·
13·	B·	12-13										1·	4·	9·	5·	15	20·	19·	13·	16·	6·	6·	3·				17, 20, 23·
13·	B·	†			34·	56·	35·	30·	1·																		10·
13	B·	36·											1·	4·	19·	27	23·	10·	3·	5·	1	2·	1·				19·
13	B·	26·												5·	11·	27	20·	13·	4·	4·	5	1·	2·	1·			19·
13	L·	45·										1·	2·	7·	25·	57	31·	17·	9·	6·	4·	3·					19·
14·	L·	45·											1·	9·	22·	29	13·	16·	8·	9·	10·	6·	3·				19, 24·
14	L	1·	1		2·	11·	46·	45·	16··	1·	1	15·	5·	6·	1	5	6·										10½, 15·, 20·
14·	B·	15·				19·	38·	50·	35·	10·	2	1·	1·			2	4·										11, 20·
14	B·	33										1·	1·	17·	41·	25·	12·	7·									18·
14·	B·	13·											2·	5·	4·	4	12·	7·	9·	15·	9·	12·	2·		1·		20, 23·, 25·
14·	B·	14,36,37							1·			1·		5·	16·	27	13·	6·	7·	4·	9·	3·		1	2	3	19·, 24
15·	B·	15,26,28								1			2·	14·	34·	20	14·	10·		1		3·					18·
15	B·	n.d.·										1·		6·	13·	29	22·	7·	3·	2·	3·	4·		1			19
16·	B·	15,26,28						1·	2·		2	8·	32·	55·	25·	4	2·	2·		3·							17·
16·	B·	33·									2·	15·	30·	35·	14·	9	9·	4·									17·
16·	B·	15·											2·	4·	6		5·	5·	10·	15·	9	10·	1	3		1½	19,23·, 25
16	B·	15,16·										1·	4·	13·	27·	32	22·	2·	1	1	2	2·					19, 24·
16	B·	14·											1	4·	10·	25	20·	13·	8·	2	4	3·					19·
16·	B·	15·				10·	28·	42·	30·	8·	12	3·		5·	8		3·	1·	1·	3·							11, 14; 19·
16·	L·	· 46·												6·	7·	33·	13·	11·	13·	14	7·	5·	1				19·, 23
16·	L	45·												7·	16·	18·	29·	18·	15·	12·	7·	10·	1				20·, 25
17·	B·	15·												3·	8·	20·	27·	29·	9·	7·	2·	2·	7				20, 25·

† "Deer Island"·   ½ 1 at 30- cm.   n.d. Not distinguished.·
2 at 31- cm.

TABLE VII. Occurrence of length "peaks" of sardine herring in 1932

In the following table "peaks" in the length-distribution in all samples of sardine herring measured by two observers (one at Blacks harbour, the other at Lubec and Eastport), are classed as "main", that is the best represented peak in a sample, or "secondary", when higher peaks occurred in the same sample. Determination of peaks can be followed in table VI, which includes an extract of the original data. In the table below the position of peaks is given to the nearest centimetre. A correction of plus 0.5 cm. is applicable throughout. "Areas" are shown in figure 5.

Week ending	Area	Main peaks	Secondary
Aug. 13......	7	18.	15.
	8	22.	19.
	15	17.	
	23	20, 21.	23.
Aug. 20......	5	16.	
	7	16, 2 at 17, 18.	
	20	20.	
	23	22.	19.
Aug. 27......	1	19, 21, 22.	16, 18, 19.
	7	18.	22.
	23	20, 2 at 22.	23.
	40-44	17, 22.	19, 21.
Sept. 3......	1	10, 15.	15.
	7	4 at 18, 5 at 19, 21.	21, 22, 2 at 23.
	8	19.	23.
	12	23.	
	13	23.	
	15	10.	
	23	24.	20.
	38	22.	
	46	6 at 19.	22, 23, 25.
Sept. 10......	5	10, 11, 18, 19.	17, 25.
	7	18, 7 at 19, 2 at 20.	16, 20, 2 at 22, 23, 24, 25.
	12 and 13	5 at 24.	
	13	2 at 20.	22, 23.
	15	11.	
	20	2 at 20.	
	46	5 at 19, 22.	

Week ending	Area	Main peaks	Secondary
Sept. 17......	1	11.	15, 20.
	3	11.	19, 24.
	7	19.	
	12	15, 25.	28.
	13	19, 20, 2 at 23.	19, 20, 3 at 25.
	14	19.	
	15	4 at 11.	2 at 14, 2 at 19, 20.
	16	20.	23.
	28	19.	
	33	17, 18.	
	36	19, 20.	
	45	2 at 19, 20.	24, 25.
	46	19, 20, 23.	21, 23, 24.
	12 and 13	20.	17, 23.
	15 and 16	19.	24.
	15, 26 and 28	17, 18.	
	14, 36 and 37	19.	24.
	N.D.	10, 19.	
Sept. 24......	7	2 at 11, 18, 2 at 19, 20.	11, 12, 15, 16, 19, 25.
	14	2 at 19, 2 at 20.	10, 18, 24, 25, 27.
	15	12, 18.	19.
	16	2 at 11, 12.	15.
	26	2 at 19.	
	33	11.	17.
	46	19.	
	⎰ 15, 16, 17, ⎱ 18, 26 and 28	12, 19.	18.
Oct. 1......	5	12.	
	11	19.	23.
	14	20.	17.
	15	2 at 12.	
	16	11.	
	23	2 at 20, 3 at 21, 23, 25.	3 at 23, 25.
	34	11, 12.	
	35	10.	
	46	2 at 20.	23, 24, 25.
	⎰ 15, 16, 17, ⎱ 18, 16 and 28	13.	
Oct. 8......	14	2 at 18, 19, 20.	20, 12.
	15	11, 2 at 12, 2 at 13.	2 at 16, 18, 19.
	16	2 at 10, 12.	17.
	20	11.	15, 19.
	23	5 at 21, 22.	
	26	2 at 19.	
	32	11, 2 at 12.	
	34	2 at 11, 9.	16, 12.
	35	11.	
	36	2 at 10, 12, 19.	27.
	46	2 at 19.	

Week ending	Area	Main peaks	Secondary
Oct. 15......	14	18, 4 at 19.	15, 25.
	15	12.	
	17	19.	
	23	2 at 21, 22, 23, 3 at 24.	21, 22, 23.
	26	12, 13, 18, 2 at 19.	13, 14, 16, 22.
	32	11, 12.	16.
	33	2 at 10.	
	34	10, 2 at 11.	
	46	22.	25, 28.
	15 or 23	12.	19.
	41, 43, 44	25.	22.
Oct. 22......	14	18.	12.
	15	10, 3 at 12.	20.
	16	19, 20.	12, 13.
	17	11, 12.	
	23	2 at 21, 22.	2 at 24, 25.
	26	12, 13, 18, 2 at 19, 20	2 at 12, 18, 19, 25.
	32	11.	
	35	2 at 11.	
	42	12.	
	41, 43, 44	21, 2 at 24, 25.	2 at 12, 16, 19, 22.
	15 and 17	12.	19.
	15, 16 and 17	12.	23.
Oct. 29......	14	11.	
	18	20.	13, 16.
	23	21, 2 at 24.	2 at 22, 23, 27, 29.
	26	18, 19.	
	27	2 at 13.	
	15-17	13.	
	18 and 26	19.	12, 22.
Nov. 5......	15	11, 3 at 12, 2 at 13, 2 at 14.	2 at 18, 2 at 19, 20, 21.
	18	21.	13, 25.
	23	2 at 22, 23.	13, 20, 25.
	26	2 at 12, 2 at 19.	12, 15, 2 at 20, 24.
	27	2 at 13, 14.	18.
	16, 17	13.	17.
	12, 14	2 at 12.	
	41, 43, 44	22, 25.	
Nov. 12......	14	10, 11, 19.	10, 2 at 19.
	15	2 at 10, 3 at 11, 2 at 12.	2 at 18.
	16	11.	
	22	22.	12.
	27	2 at 13.	16, 18.
	17, 18, 26, 28	19.	23.
	15, 16, 17, 18, 26 and 28	11.	15.
	N.D.	11.	

Week ending	Area	Main peaks	Secondary
Nov. 19......	14	2 at 18.	10, 11.
	15	6 at 11, 12.	
	16	10, 12.	19.
	18	13.	19.
	22	2 at 21.	19, 2 at 25.
	23	20.	13, 23.
	26	12, 13.	11, 15, 2 at 18, 23.
	27	12.	
	15, 16, 17, 18, 26 and 28	11, 13.	10, 25.
Nov. 26......	14	10.	
	15	3 at 11, 2 at 12.	19.
	16	10, 11, 12.	2 at 19, 22.
	18	2 at 12, 13.	15, 18.
	22	18.	16, 21, 26.
Dec. 3......	15	10, 2 at 11, 12. 13.	
	16	3 at 11, 3 at 12, 14.	13, 17.
	18	12, 2 at 13.	16.
Dec. 10......	15	3 at 11, 12.	
	16	2 at 11, 12, 13.	
Dec. 17......	15	3 at 11, 12, 13.	
	16	12, 13.	

TABLE VIII. Length of sardines, 1932

The table gives the number of occurrences of peaks in length-frequency distributions arranged by fortnights and centimetres length.   0.5 should be added to the length (which was measured to the "cm. below").   Samples (from Blacks harbour, Lubec and Eastport) of all purchases reaching the factories where the two observers were stationed.   Measuring only began in August.

Number of peaks at (cm.):	Fortnight ending:									
	Aug. 20	Sept. 3	Sept. 17	Oct. 1	Oct. 15	Oct. 29	Nov. 12	Nov. 26	Dec. 10	(Dec. 16)
9	..	..	..	..	..	..	..	..	..	..
9	..	..	..	..	1	..	..	..	..	..
10	..	2	2	2	7	1	4	5	1	..
11	..	..	8	8	9	5	8	13	10	3
12	..	..	..	8	12	15	11	9	7	2
13	..	..	..	1	4	6	9	5	5	2
14	..	..	2	..	1	..	3	..	1	..
15	1	2	2	2	2	..	2	2	..	..
16	2	1	1	1	5	2	1	1	1	..
17	3	1	4	2	1	..	1	..	1	..
18	2	6	4	4	5	4	6	6	..	..
19	2	15	28	11	16	8	8	6	..	..
20	2	2	16	8	2	4	4	1	..	..
21	1	4	1	3	8	4	2	3	..	..
22	2	8	4	..	6	5	4	1	..	..
23	1	7	8	6	2	2	2	2	..	..
24	..	1	11	2	3	6	1	..	..	..
25	..	1	7	5	3	3	3	3	..	..
26	..	..	..	..	..	..	..	1	..	..
27	..	..	..	1	1	1	..	..	..	..
28	..	..	1	..	1	..	..	..	..	..
29	..	..	..	..	..	1	..	..	..	..
Total......	16	50	99	64	89	67	69	58	26	7

TABLE IX. Comparison of sardine fishery in Quoddy and Grand Manan

Q. "Quoddy". Areas 12-18, 22-37.
G.M. Grand Manan. Areas 39-44, 50.

1927			1929		
Fortnight ending	Q	G.M.	Fortnight ending	Q	G.M.
May 22	16	0	Mar. 30	14	0
June 5	52	0	April 13	30	1
19	35	1	27	45	9
July 3	30	0	May 11	134	0
17	102	3	25	145	2
31	102	4	June 8	116	3
Aug. 14	118	2	22	108	8
28	93	3	July 6	49	8
Sept. 11	74	0	20	104	8
25	97	0	Aug. 3	70	9
Oct. 9	71	0	17	120	11
23	64	3	31	65	0
Nov. 6	82	4	Sept. 14	107	12
20	71	0	28	129	11
Dec. 4	48	0	Oct. 12	106	5
			26	56	10
			Nov. 9	25	1
			23	12	3

140

TABLE X. Hours of fog recorded at Light Stations in July 1930, 1931
(By courtesy of Canadian and U.S. Marine Departments)

	1930 Hours	1931 Hours		1930 Hours	1931 Hours
Cape d'Espoir	51*	93†	Long Eddy point	253	354
East point	37*	39†	Letite passage (Mascabin		
Entry island	56*	99†	(Green) pt)..	237	316
Cape north	73	123	Head harbour(East Quoddy)	295	355
Flint island	130	246	West Quoddy head	299	439
Cranberry island	220	445	Libby islands	323	359
Beaver island	328	446	Egg rock	96	145
Sambro	319	292	Petit Manan	203	308
Halifax (Sambro) lightship	208	288	Mount Desert	209	265
Cross island	350	376	Matincus rock	101	188
Cape Roseway	480	446	Owls head	93	243
Seal island	246	403	Seguin	96	244
Cape Fourchu	342	344	Cape Ann	40	128
Brier island	292	344	Cape Cod	25	165
Gannet rock	314	402	Vineyard sound	47	188
Point Prim	137	137	Block island S.E.	39	232
Cape d'Or	313	278	Great Salt pond	22	154
Apple river	201	298	Montauk point	62	207
Cape Enrage	206	301	Sandy Hook	23	32
Cape Spencer	299	362	Fenwick island	0	41
Lepreau	224	353			

*For the year 1929.   †For the year 1930.

Mixing and Residual Currents in Tidal Waters as Illustrated in the Bay of Fundy

By E. E. Watson

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Woods Hole Oceanographic Institution

ABSTRACT

(1) The Saint John estuarial water flows out to sea as a strongly stratified layer, about 10 metres thick, retaining its lower boundary as far as Grand Manan island, a distance of 74 km. Persistence is due to the high density gradient combined with the low velocity gradient through the layer as it flows out over the deep homogeneous water. (2) The homogeneity produced in shoal water by tidal stirring excludes permanent residual currents if sufficient light water is available, the outward gravity force balancing the inward dynamic force of the peripheral current. (3) Where the waters of the bay shoal gradually the turbulent influence of bottom friction extends upward 20 to 50 metres, causing the isosteric surfaces to bend downward as they come within this distance from the bottom, but for a steep rise of the bottom the isosteres continue horizontally to meet it. (4) There are found in juxtaposition (a) stratified regions where tidal mixing causes an outflow of mixed water at an intermediate depth with an inflow both at surface and bottom, and (b) regions where a local supply of fresh water is mixed with salter water and flows away at the surface, with a compensating inflow at bottom only. (5) Calculation shows that of the total mixing in the bay of Fundy that is effective in producing a circulation, 3% occurs in the Saint John estuary, 6% in the Quoddy passages and 14% at the head of the bay.

PREFACE

The following paper on the physical oceanography of the bay of Fundy is one of a group of four, published by the investigators of the International Passamaquoddy Fisheries Commission. The subjects and authors of the other papers are: the phytoplankton by Dr. H. H. Gran and Mr. Trygve Braarud (1935), the zooplankton by Dr. Charles J. Fish and Dr. Martin Johnson (unpub.), and the herring by Mr. Michael Graham (1936).

All the titrations and many of the original observations were ably carried out by Mr. Charles J. Hughes at St. Andrews, N.B. During the winter of 1932-33 leave of absence from Queen's University was kindly granted to the writer and the work of reducing the observations was carried on at Woods Hole. The preparation of the paper has taken considerable time and has been made possible chiefly through the assistance and facilities offered by the Woods Hole Oceanographic Institution. To Dr. H. B. Bigelow and to other members of the Institu-

141

142

tion, as well as to Dr. A. G. Huntsman and the investigators of the Commission, I am indebted for many profitable suggestions. It is also a pleasure to thank Mr. K. G. Chisholm of the Water Power and Hydrometric Bureau at Halifax for information on drainage, and Mr. Dexter P. Cooper for the use of blueprints of the Quoddy Project.

CONTENTS

PART I. GENERAL INTRODUCTION

1. HISTORY AND EQUIPMENT

The bay of Fundy is well known for its extreme tidal range. To the oceanographer it presents a problem in which turbulence phenomena are of paramount importance. Our knowledge of oceanic turbulence is so limited that the water movements in this bay cannot be derived satisfactorily from the usual hydrographic observations. In many parts the balance between static and dynamic

forces is too delicate to admit of simple solution by analyses based on occasional observations. The obvious dominant movement is that of the tidal oscillation, but in addition there is an equally important progressive movement which on the surface consists of a counter-clockwise circulation around the bay. Considerable knowledge of this circulation has been gained by the Biological Board of Canada from its station at St. Andrews, N.B., but unfortunately much of the information collected has never been published. A few papers by A. G. Huntsman and two by J. W. Mavor (1922, 1923) in addition to the publications of W. Bell Dawson and the Canadian Hydrographic Service furnish nearly all of the available knowledge of the physical oceanography of the bay of Fundy.

The data and results presented in this paper were obtained as the hydrographic part of the investigations of the International Passamaquoddy Fisheries Commission. The object of this Commission was to determine the probable effect on the fisheries of the construction and operation of the Cooper Quoddy Project, a proposed tidal power project involving the damming of Passamaquoddy and Cobscook bays. Hence the hydrographical part of the investigation was concerned primarily with determining the part now played by the Passamaquoddy mixing mechanism and with estimating the changes which might be brought about by the construction of the dams. The period of the investigation covered the summers of 1931 and 1932, but as all the data from the first year were destroyed by fire the observations presented cover a single year only. Since the boats used were shared by the plankton investigators they were not always available for hydrographic work and the program of each investigator had to be suited to the needs of others. On the other hand the contemporary study of the plankton and hydrography was of mutual advantage.

The two boats used in the hydrographical work were the U.S. Bureau of Fisheries' "Pelican" and the Biological Board of Canada's "Prince". Neither boat was large enough to stand bad weather in the open sea and the "Prince" was in a condition suitable only for use near shore. Samples were collected by means of Knudsen water-bottles and titrated in the laboratory by the standard Mohr method. Temperatures were measured by Schmidt or Richter and Weiss thermometers calibrated in tenths of a degree and read by means of a lens mounted in a holder, hundredths of a degree being estimated. In general two thermometers were used on each bottle. When possible both boats were used so that simultaneous observations could be made along two sections. When only one boat was at work successive sections were made on the same phase of the tide, usually at low water. For longer sections, occupying all or the greater part of a tidal period, there was of course no object in doing this.

2. Topography

The bay of Fundy extends in a north-easterly direction from the gulf of Maine, and lies between the Canadian provinces of New Brunswick and Nova Scotia. Excluding the funnel-shaped mouth of the bay, its length is about 120 miles (220 km.) and its average width about 30 miles (56 km.).* As can be

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*All distances at sea are measured in nautical miles. 1 sea mile = 1.15 land miles = 1.85 kilometres.

4

144

seen from the bathymetric chart in figure 1, the depth increases fairly uniformly towards the gulf of Maine. The deepest channel connecting the bay to the gulf is about 150 metres deep, while within the bay there is an area of about 460 square (statute) miles (ca. 1600 sq. km.) whose depth is between 150 and 200 metres. Between the western edge of this deep basin and Grand Manan island there is a region of ledges, shoals and rocks, where heavy tidal rips are found, particularly on the ebb. The most important of the marginal features are the two arms at the head of the bay where the tide reaches its maximum range, the Saint John river with its large contribution of fresh water, and Passamaquoddy bay with its intense tidal mixing.

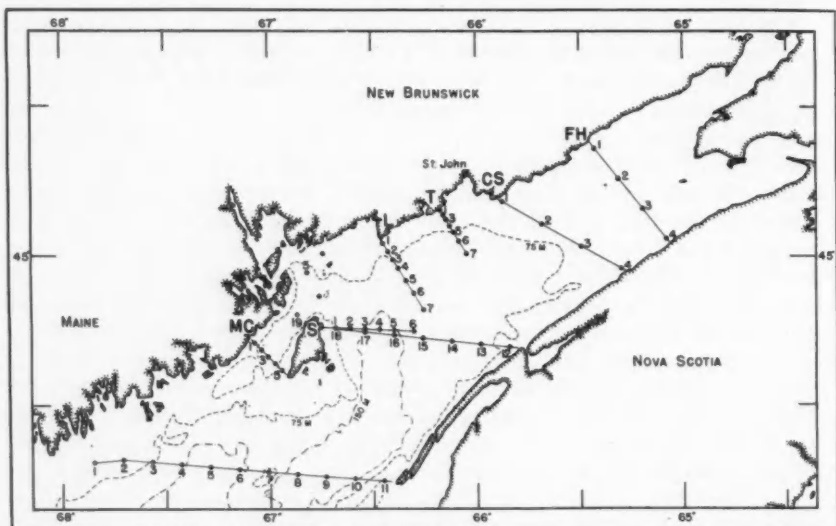A good description of the geology of the region has been given by Johnson

FIGURE 1. Bay of Fundy. Bathymetric chart and key to stations.

(1925). The most striking features of the coast line are the rectilinear shorelines of the south-eastern side of the bay and of Grand Manan channel, contrasted with the irregular drowned valley type of shore on the northeastern side below Saint John. It is important from the oceanographic viewpoint to know that these straight shorelines are not headlands which have been cut back under wave attack and which are now in the mature stage of shoreline evolution. According to Johnson the bay of Fundy is a broad Triassic lowland well worn down and deeply submerged. The southeastern coast is the projecting edge of a prominent lava sheet, forming a trap ridge, while Annapolis basin and St. Mary bay belong to a submerged valley eroded on the strip of weak sandstones exposed between the lava sheet and the nearby crystallines. On the New Brunswick side the bold shore from Quaco to Salisbury bay and its continuation from West Quoddy head to Machias bay represents a fault-line scarp now much

worn by erosion, against which the sea came to rest after the submergence of the Acadian Triassic Lowland.

Mavor (1922) gives a detailed description of the physical features of the bay, including a sketch of the bottom deposits as given on the charts of the region. The distribution of mud is interesting, for after being brought to the sea by the rivers its precipitation is sufficiently slow for it to indicate the general trend of the currents in the vicinity of the point of entry. It is well known (Gibson 1933, page 259) that a suspension of mud in fresh water will be precipitated on mixing with sea water. The settlement of the heavier or larger particles may be little affected by a saline solution, but the clearing of the solution is accelerated by the coagulation of the finer particles. From experiments it appears that a silt mixture will precipitate and clear about seven times as quickly in sea water as in fresh water. If there is strong tidal turbulence, however, the settling will not take place until a region is reached where the waters are relatively quiet. Thus the presence of mud on the bottom denotes the passage of water from the rivers, together with an absence of any great turbulence. For example, the occurrence of mud from the mouth of the Saint John river to the Quoddy region, with a narrow branch stretching down the east side of Grand Manan island, is good evidence of the general counter-clockwise circulation, but the absence of mud in Grand Manan channel is due to the strong currents there and does not in itself prove that all the Saint John water passes to the east of Grand Manan. It is necessary to complete this discussion on the distribution of mud by giving Johnson's explanation of the formation of the extensive silt deposits in the reclaimed marshland at the head of the bay of Fundy.

"The source of the silts . . . is to be found in the relatively weak red sandstones and shales which border and presumably underlie the Fundy lowland. . . . As the sea worked over this material, part of it was doubtless carried out to deep water, but a large part was always shifted towards the head of the embayment by tidal currents, and there deposited during slack water. Continued subsidence caused the sea to rework and shift northward the tidal deposits as well as the subaerial deposits with the result that we find at the present head of the Bay of Fundy material from the entire lowland repeatedly shifted northward from successive heads of the Bay as the land sank."

It is clear from this that tidal scouring keeps the bottom clean except for regions where the deposition of silt is going on at present, presumably from the river outflow. The turbidity and sharply marked boundary of the Saint John outflow are commonly observed. On July 12, 1932, when the outflow was relatively small, Secchi disc readings taken by Graham gave a visibility depth of only 4 metres at a point 9 miles (16.7 km.) SSW of St. John, whereas at a point 15 miles (28 km.) SXE from Saint John, the depth was 12 metres. These two readings, though taken only 10 miles (18 km.) apart were respectively the lowest and highest which he obtained within the coastal waters of the bay. Since the origin of the mud on the bottom of the bay is recent it seems valid to use it as evidence of the path taken by the river water.

3. WATERSHED

Through the kindness of Mr. K. G. Chisholm, District Hydraulic Engineer, considerable hydrometric data has been made available for studying the fresh

water drainage into the bay of Fundy. Figure 3 gives a table of the average monthly discharge from each of the seven drainage areas tributary to the bay of Fundy, as well as the total discharge into the bay for each month. The watershed for the bay of Fundy is 31,500 square miles (81,600 sq. km.), while for the whole gulf of Maine it is only about twice that area. Thus a great part
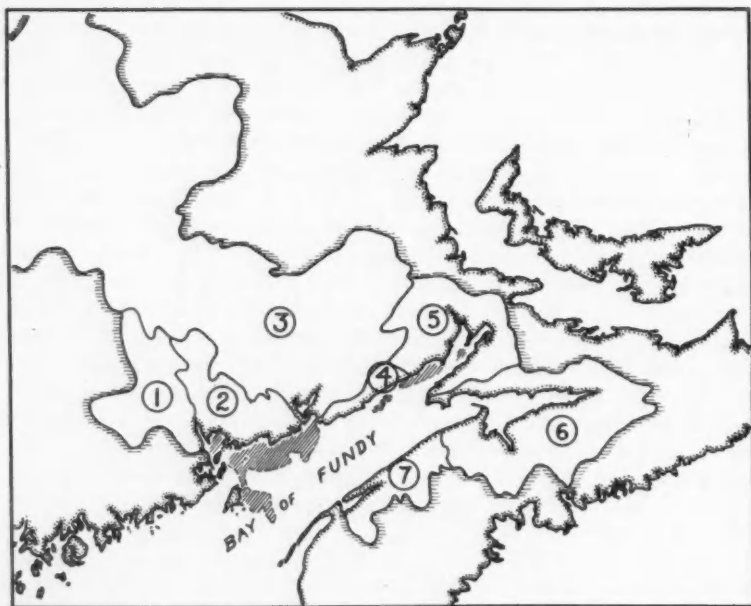

FIGURE 2. Drainage areas (numbered) and mud deposits in the bay (diagonal hatching).

AVERAGE RATES OF DISCHARGE IN CU.FT./SEC. OF THE REGIONS TRIBUTARY TO THE BAY OF FUNDY

REGION	AREA	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	YEAR
1. ST.CROIX	1,500	1,965	2,040	1,965	1,860	1,710	2,565	4,965	4,065	2,130	1,830	1,755	1,695	2,325
2. MAGAGUADAVIC	1,050	1,911	2,320	2,089	1,375	869	2,373	6,930	3,675	1,606	1,102	672	703	2,089
3. ST.JOHN	21,500	24,500	37,620	20,420	15,330	8,600	13,970	77,200	110,700	39,550	21,280	14,840	14,680	33,100
4. NORTH SHORE	960	2,342	2,563	2,630	2,276	1,181	3,110	6,807	3,264	1,335	1,104	1,075	1,095	2,295
5. CHIGNECTO BAY	2,160	4,600	3,844	4,495	5,573	3,391	5,465	14,770	9,800	2,721	1,642	1,642	1,334	4,795
6. MINAS BASIN	3,300	6,400	8,188	11,290	11,420	6,630	11,920	30,730	11,720	4,422	3,696	3,267	3,433	8,448
7. SOUTH SHORE	986	1,519	2,210	3,313	3,796	2,485	4,073	4,674	2,407	1,065	878	838	927	2,348
TOTAL INTO BAY OF FUNDY	31,456	43,237	58,780	46,800	39,630	25,047	43,476	136,076	146,331	52,829	31,532	24,089	24,007	55,400

FIGURE 3. Table of average rates of discharge for each drainage area.

of the fresh water contributed to the gulf of Maine comes to it from the bay of Fundy. In February and March the fresh water flowing into the bay is small and there is little difference in salinity between the bay of Fundy and the neighbouring part of the gulf of Maine. But in the early spring the snow and ice begin to melt, the rivers become swollen, and there is a great discharge of fresh water known as the spring freshets. The time of occurrence and the duration

of these freshets vary from year to year and from one river to another, but they usually occur in April and May. At this time the Saint John river alone has an average outflow of about 94,000 cu. ft. (ca. 2700 cu. m.) per sec. To illustrate the amount of fresh water contributed, consider the region of the bay north of a line joining W. Quoddy head to Digby gut, an area of about 4330 sq. (statute) miles (11,200 sq. km.). If all the fresh water flowing into this area during April and May were to accumulate it would form a layer over 6 feet (1.8 m.) deep. Of course this water is not all retained in the bay or accumulated on the surface, for it is dissipated both by vertical mixing and by outflow to the gulf of Maine. But both these processes are slow, and not only does the bay of Fundy remain fresher than the gulf of Maine throughout the summer but also the whole character of the water movements is affected by the presence of this fresh surface layer. (See part II, sects. 4 and 5). In certain restricted regions of the bay of Fundy the concentration of freshet water is even greater than that quoted for the major part of the bay. For example, in the single month of April, 1932, the discharge of freshet water into Passamaquoddy bay was equivalent to a layer nearly 14 feet (4.3 m.) deep over its area of 100 sq. (statute) miles (260 sq. km.). The variation of the time of occurrence of the maximum freshets is shown in figure 4 in which the monthly discharge of the Saint John river, measured at Pokiok, N.B., is plotted for the years 1922, 1930, 1932. The year 1922 must have had a very late spring, for instead of the usual freshets in April and May the discharge in April was less than usual, in May very much less, and in June, when the freshets are usually over, the maximum monthly discharge occurred. 1930 and 1932 are typical years showing maxima in May and April respectively. The freshets from the shorter rivers naturally tend to be earlier than those from the Saint John, but the latter may safely be taken as an index for the whole region. Figure 5 shows the monthly discharge into Passamaquoddy bay during 1932 and also the mean monthly discharge for a number of years. The variation of the discharge in the Saint John river from one time to another is best illustrated by the graphs in figure 6, which show the daily discharge during the freshet month of April and also during the summer month of July. The rate of dispersal of this fresh water on entering the bay will depend on the tidal conditions at the time, as well as on the winds, so that the resulting distribution of salinity and temperature at a certain time of the year may differ considerably from one year to another, and even the change from day to day may be quite rapid.

4. TIDAL EFFECTS

General information on the tides may be found in the publications of Dawson (1920) and Marmer (1926, 1928, 1932). The tides in bays are of two types: the progressive wave, with high water progressively later and the range decreasing from mouth to head; and the stationary wave in which there is little or no difference in the time of high water throughout the bay, and the range increases from mouth to head. For the stationary type to occur it is necessary that the dimensions of the bay shall be such that the natural period of oscillation of the water shall be very nearly equal to the period of the tidal movement outside the
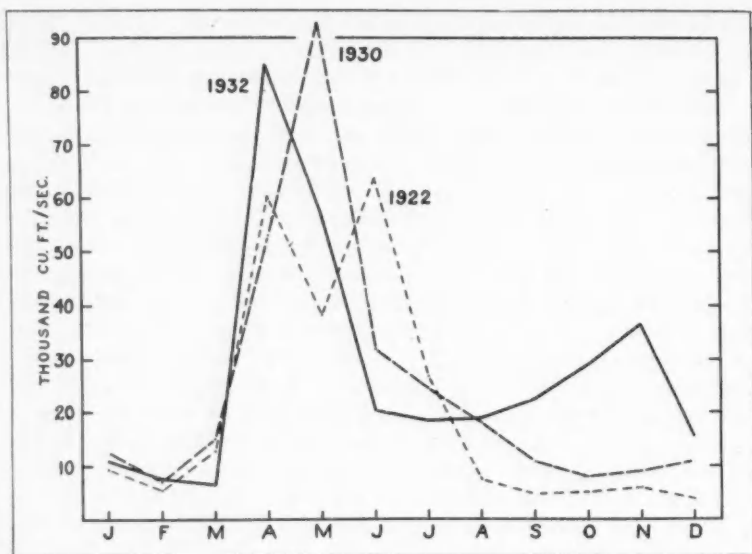
FIGURE 4. Monthly discharge of Saint John river, showing variations in the time of spring freshets.
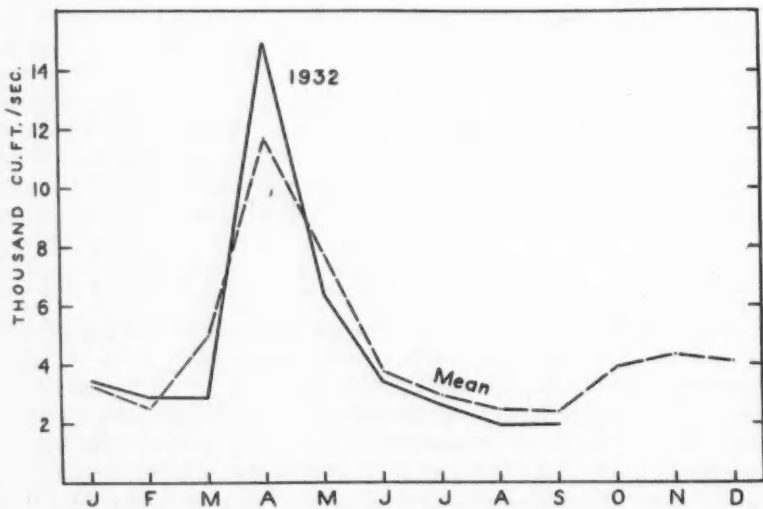

FIGURE 5. Monthly discharge into Passamaquoddy bay.

bay. This is the case in the bay of Fundy where the natural period of oscillation is about 12 hours. There is only 6 minutes difference in the time of high water from Machias Seal island to Isle Haute, 100 miles (185 km.) apart, yet the tidal range is doubled. Another important feature of the stationary wave tide is that slack water occurs at or near high and low water, and the current is strongest at half flood and half ebb. This has an important bearing on the comparative range of the tide on opposite sides of the bay. When the tidal wave is progressive the range on one shore is greater than on the other, but if slack water occurs at high and low water, as with a standing wave, there can be no effect of the
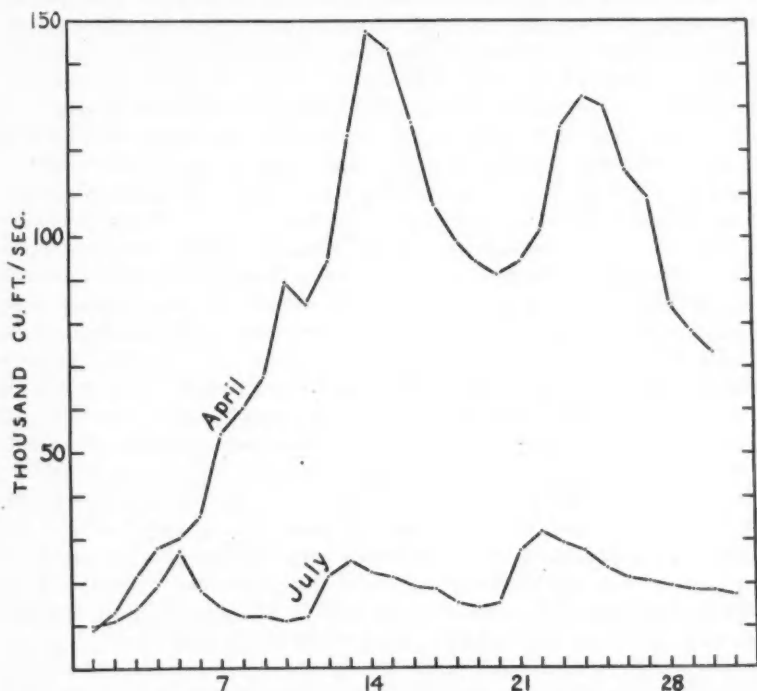
FIGURE 6. Daily discharge of Saint John river at Pokiok, N.B., for April and July, 1932.

earth's rotation at these times and the range will be the same at opposite points on either shore. In the bay of Fundy the range on the southern shore is only slightly greater than on the northern, so that the tide is undoubtedly of the standing wave type.

According to Dawson's tidal current measurements in the bay "the current is as strong down to a depth of 30 fathoms as it is on the surface, and at most places it turns in direction on the surface and below at practically the same time." This means that the currents are quite strong near the bottom and the irregularities of the bottom generate eddies which break down the natural

stratification for a considerable height above the bottom. In the upper part of the bay this turbulence reaches to the surface and as a result the water is homogeneous from surface to bottom. Indeed the waters here never become stratified, since they are naturally homogeneous at the end of the winter, and the intense tidal stirring never ceases, so that the vernal warming never gets a chance to build up surface layers of sufficient stability to withstand the eddies.

As might be expected the bay of Fundy furnishes examples of every type of tidal mixing. The characteristic feature of the one just mentioned is that there is a sufficiently large body of turbulent water that the tidal ebb and flow does not introduce an appreciable quantity of stratified water from the neighbouring regions. Probably the head of a tidal bay is the only situation where this can occur. In other types of tidal mixing the mixing region is more localized with respect to the water that passes over it. We shall consider three such types which we shall call Quoddy mixing, shoal mixing, and passage mixing. In the Quoddy region of the bay of Fundy there are two land locked bays, Passamaquoddy and Cobscook, whose joint area is about 140 square miles (360 sq. km.). The tide runs in and out of these bays through two long narrow channels in which there is great turbulence and consequent mixing. At one end of the mixing channels are the restricted waters of the bays while at the other end is the open Fundy water. The result is an efficient mechanism for breaking down the stratification of a large volume of water. In shoal mixing we have tidal streams flowing from deep water over one or more shoals with a consequent variation of velocity. Eddy formation is facilitated by decreasing velocities as well as by the large irregularities of an uneven but shallow bottom. A series of shoals such as those off the SE coast of Grand Manan island will have a cumulative mixing effect which is noticeable locally rather than in the surrounding region. There is no continuous addition of fresh water within the region to accelerate the removal of mixed water. In the case of the Manan shoals the surface water at the NE end is lighter than at the S end, so that a horizontal density gradient is established. The resulting residual surface flow across the region is less than it would be if the shoals were absent. During a single tidal movement, flood or ebb, the transport of water across the shoals is not as large as the surface velocities might suggest, because the depth of water above the shoals is very small, while the motion of the deeper water between shoals is almost entirely rotational. Turbulence is so great that the vertical mixing at any one place is almost complete and the isosteres slope steeply downward from surface to bottom. The residual surface flow is a slow movement of water which gets progressively heavier instead of a current of water traceable by constant characteristics. To supply the heavy water for this progressive mixing there must be a bottom inflow to the region, but this movement will be so slow as to be masked by seasonal changes. The mixing produced by a small isolated bank such as Grand Manan bank will be scarcely noticeable either on the bank or around it. Turbulence will occur only in a small region on the down stream side of it and the veering of the tidal stream shifts this region around. Consequently the resulting mixing will not be cumulative and its effect on the density distributions will be scarcely observable. The most noticeable effect of

the bank is an increased choppiness of the water due to its higher velocity. The surface water will also be colder and heavier than it is away from the bank, not because it is mixed but because the heavier sub-surface water has been carried up the slope of the bank by its greater momentum, displacing the lighter surface water from the area above the bank. After passing the bank, this heavier water will sink again to its normal level and if the density gradient of the surface waters is strong a line of convergence may occur where the sinking water meets and flows beneath the lighter layer. The writer has frequently observed this convergence on a small scale in the St. Croix river estuary. At Joe's point, where the estuary is opening out into Passamaquoddy bay there is a sand bar or shoal running out beneath the water for some distance. On the flood tide a sharp line of convergence may be seen where the heavier water brought up over the bar sinks again beneath the lighter water. The convergence is marked not only by a line of scum and floating material, but also by a difference in colour on either side. In addition when there is a light breeze against the tide the heavy water will be strongly rippled while the lighter water remains smooth. It is possible to measure the slope of the sinking water by observing the constant distance beyond the convergence line at which a two metre depth drag will remain. While such phenomena as these may be produced by an isolated bank, the mixing effects are undoubtedly small. The case of a large bank, such as Georges bank, is too complex for discussion here and will be dealt with later (Part III, sect. 2). The third type of local tidal mixing occurs in passages connecting two bodies of tidal water, as for example the passages between St. Mary bay and the bay of Fundy. Such passages are usually shallow and produce a mixing of the superficial layers which can be only of local importance. Deeper and wider channels such as Grand Manan channel must be studied individually.

There is a secondary effect of the tidal currents along broken shores which should be mentioned. If any mixing takes place along-shore the surface water will be heavier there than further off shore. Consequently there will be a slow surface current towards the shore and a sub-surface flow away from it. These currents will only be small components which are additive to the tidal current along-shore, but they may be of importance in causing drift bottles to go ashore.

5. WIND EFFECTS

The general theory of wind driven currents in homogeneous water remote from obstructions has been worked out by Ekman. Account has been taken of the gradient currents and the bottom currents which arise with a wind blowing parallel to a coast. More recently Ekman has also developed the theory for the effect on the current field of the configuration of the sea bottom. In general a counter clockwise vortex tends to form where the depth increases in the direction of the current and a clockwise one where the depth decreases, while there is no disturbance where the current follows the contours. This effect is not restricted to wind currents but occurs with any gradient current however formed. An enclosed sea introduces boundary conditions which modify Ekman's results for wind currents considerably. Palmén (1930) has studied the wind driven currents in the gulf of Finland and shows how the velocities may be calculated from the

resulting solenoidal field. Although he pays particular attention to winds parallel to the gulf, he also gives data for the velocity and deviation of currents produced by winds in all directions. From his results it appears that the range of wind directions which produce an inward component of surface current is only 140°, while winds from the remaining 220° produce an outward drift. This inequality in directions is due to the fact that water can not move to the right of the wind if the sea on the right is enclosed but will do so freely if it is open. Sandström (1919) gives a good account of the various possible effects of wind on currents, both in restricted basins and in the open sea. Harvey (1928) also reviews the effects of wind in shallow and enclosed seas. Illustrating the fact that the depth of a wind blown current is dependent on the homogeneity of the water he says "in the southern part of the North Sea strong tidal streams in the shallower water with uneven bottom set up increased turbulence in the water, which is here homogeneous, and in these areas wind-blown currents extend deeper and appear more effective in transporting planktonic organisms."

An important factor in the consideration of wind blown currents is the length of time required for their formation. During the period of acceleration the velocities will differ from their final steady value. In an enclosed sea the transport of surface water to the right of the wind builds up a pressure gradient at right angles to the wind and this in turn produces a deep gradient current in the same direction as the wind. If the steady state is reached there will no longer be any movement of the surface water to the right of the wind, unless there is a compensation current along the bottom to the left of the wind direction. Whether this occurs will depend on the stability of the water and the force of the wind. It is evidenced by upwelling of cold bottom water along the shore on the left of the wind direction. This latter phenomenon is of course frequently observed with an off-shore wind (Bigelow 1927, p. 588) but it can also occur on a shoreline parallel to the wind direction and to the left of it, as in the case at present under discussion. Since the direction of the wind blown current approaches that of the wind as the steady state is attained and since its final direction is dependent on the stability of the water layers, the time to establish a steady wind drift is of primary importance. Ekman calculates for the open sea above the continental shelf that the stationary state is established in a few days time, but that the surface current is established in a few hours time and responds quickly to changes in wind. In an enclosed sea, however, the boundary conditions compel an immediate dependence of the surface current on the deep gradient current, so that it will probably take one or two days for the wind driven currents to reach a steady state. It is to be noted that Palmén's observations which show the dependence of the solenoidal field on the wind are taken only when the wind has been reasonably constant for three days. If the region under consideration is not subject to steady winds for days at a time the wind driven currents will not be as important as those observed by Palmén.

If we now examine the available wind data for the bay of Fundy, we shall see that except for unusual gales the wind is only of secondary importance in determining the solenoidal field and the currents. Figure 7 shows the total mileage of wind from each direction during each month in 1932, as observed at

point Lepreau, N.B., and at Yarmouth, N.S. Unfortunately there are no published data (other than the daily weather maps) from which one can obtain the duration and constancy of the wind from a particular direction. It has
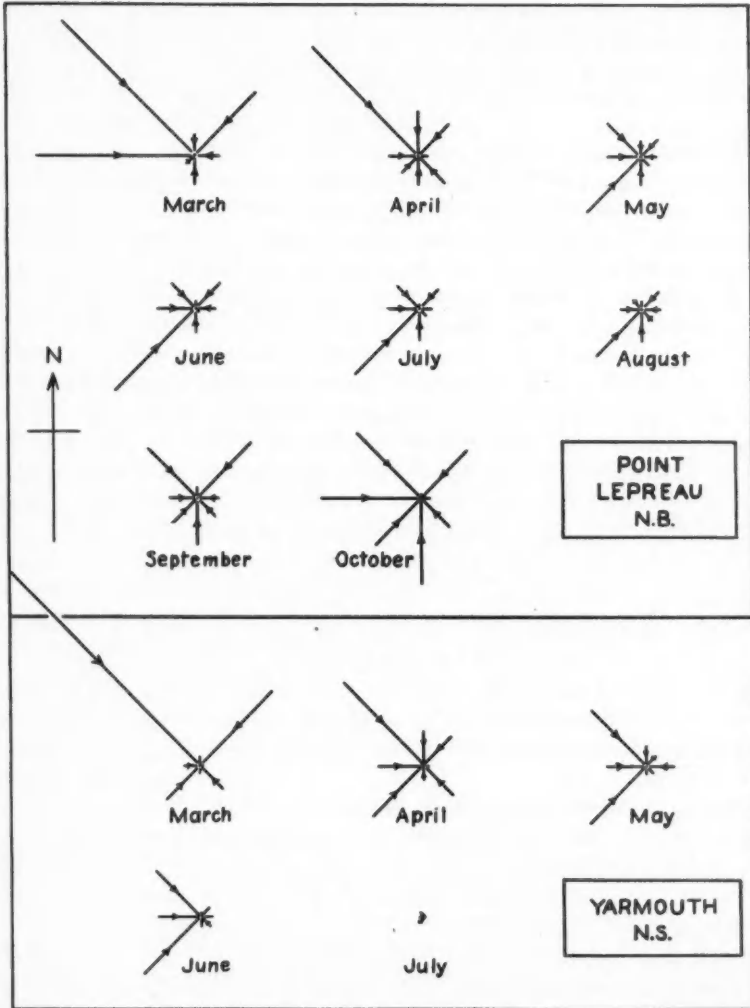

FIGURE 7. Monthly wind mileage in 1932 at Lepreau and at Yarmouth. (The NE wind mileage in September is approx. 2000 miles).

been the writer's experience in the bay of Fundy during the summer months that the wind increases during the day and then decreases after sunset. Furthermore there are often marked changes in the wind direction near the coast.

Data for the frequency of winds in the gulf of Maine and their effect on the circulation are given by Bigelow (1927, pp. 962-970). The Fundy winds are much the same as in the gulf of Maine, northwesterly in winter and south-westerly in summer. The chief points of difference in the bay of Fundy are the shallower depth and resulting homogeneity and the more complete enclosure of the surface layers. The influence of the diurnal warming and cooling of the land also produces a greater variation in the Fundy winds. On the basis of Palmén's observations it seems probable that winds from the S, SW and W will produce a surface drift into the bay while winds from the NW, N, NE, E and SE will drive surface water out of the bay. There may of course be a hori-zontal circulation as well as a vertical one, and the wind drift referred to is the resultant surface drift in or out across the whole width of the bay. Bigelow's deductions for the wind driven currents in the neighbouring part of the gulf of Maine are as follows. In summer the prevailing winds will drive surface water from the gulf towards Nova Scotia with a resultant movement northerly into the bay of Fundy. This is well borne out by drift bottle results. On the Maine coast east of Mount Desert there is a compensating outward flow which is against the prevailing wind. It is possible that the stability may be sufficiently low to allow of upwelling and a vertical circulation when the offshore winds are sufficiently strong. He also suggests that the tail of low salinity water from the Saint John river southward in April may be caused by the northwest winds.

Since it is well known that the bay of Fundy contains water that is homo-geneous it would seem to be especially susceptible to the effects of winds. How-ever, an examination of the observations will show that only certain regions are homogeneous, while others are unusually stable in the surface layers as a result of the inflow of fresh water from the rivers. Wind effects may predominate in the water at the head of the bay and perhaps in the Grand Manan channel region, but the main circulation of the bay is undoubtedly due to gravity forces. The wind is mainly responsible for the confusing complexities which cause such differences in detail between sets of observations which one would otherwise expect to agree.

There is no doubt that winds of unusual strength and duration may have a very great effect in the bay of Fundy. In particular such a wind from the NE in the summer would drive surface water out into the gulf of Maine, with a compensating indraught of bottom water. If a storm centre passes over southern New Brunswick the wind will blow up the bay and increase the tide, but if it passes over Nova Scotia or further east the wind will blow out of the bay. The most striking case was the famous Saxby tide of October 5, 1869. A severe gale up the bay occurred on a day when the moon was new and also in perigee, with the result that at high water the level in Cumberland basin was raised 6.2 feet above the normal height at perigee springs (Dawson 1920, p. 27). It is of interest to note that at the succeeding low water the level fell as much below ordinary low water as it had been raised above ordinary high water (Dawson 1917, p. 92).

6. THE DETERMINATION OF THE RESIDUAL CURRENTS

The residual currents in the bay of Fundy are unusually difficult to detect because of the predominance of the tidal currents. While the latter are of importance to navigation the residual currents control the interchange of plankton, nutrient salts and heat energy between the bay and the neighbouring gulf of Maine. The methods available for the determination of these currents are:

(a) the vectorial analysis of current velocities measured over a tidal cycle,

(b) the charting of drift-bottles returns,

(c) the interpretation of horizontal and vertical sections showing the temperature, salinity and density distribution,

(d) the use of T-S diagrams to trace the history of the water,

(e) the calculation of dynamic heights and the charting of dynamic isobaths,

(f) the correlation of physical observations with biological evidence.

We shall discuss each of these methods with regard to its application to the bay of Fundy, and show why no one method has yet been able to give a satisfactory solution.

Current measurements by Dawson (1908) at various points in the bay led him to the conclusion that there was no general movement of the water in any one direction which was at all well marked. However, Mavor (1922) has shown from these same measurements that there is a definite displacement of the water at the end of a tidal cycle. By using the average velocity during each hour and adding the corresponding displacements graphically the resultant displacement is easily obtained. Mavor determined this for each of Dawson's stations. It should be pointed out that the vectorial addition of the hourly displacements is only valid if the velocity of the particular water particle under consideration is at every instant the same as the velocity of the water measured at the anchored ship. This is approximately true in regions far from shore where the bottom is uniform, but in so small and irregular a region as the bay of Fundy there are great differences in the currents at points quite close together. Consequently it is unwise to place too much reliance on the quantitative results which Mavor obtains in this way.

The analysis of surface currents by drift bottle returns has been widely used, but it is a method which can be misleading unless the greatest caution is used in interpreting the returns. The finding of a bottle is the result of a number of chances among which are the simultaneous occurrence of a beach and an on-shore wind. In the absence of wind there is a shoreward movement of the surface waters wherever there is strong tidal mixing along shore, so that in such places the bottles will tend to get broken or to be stranded where they will not be found. Bigelow (1927, page 867), in discussing the validity of these returns, mentions the fact that the drift of a bottle does not necessarily reproduce the drift that would have been followed by a particle of water, because the bottle floats on the surface, while the water may sink as new water rises from below to take its place. This is of particular importance in the bay of Fundy where the stability is low and vertical circulation does take place. A good account of drift bottle experiments during August and September is given by Mavor (1922).

The distribution of temperature and salinity is commonly used to trace the movements of sea water. This is possible because the concentration gradients in the sea are usually so small that the effects of diffusion are practically negligible. Indeed it is now recognized that the changes in concentration or temperature which do take place are due not to molecular diffusion but to eddy viscosity. The normal distribution of sea water at rest would be a horizontal stratification with density increasing with depth. Any motion of the water tends to disturb this distribution in such a way that gravity forces are produced to balance the dynamic forces of the moving water. If a steady state is reached we may deduce the motion of the water by observing the distribution of the density. The separate variants of temperature and salinity help to identify and trace the moving bodies of water. Unfortunately the movements of the water become so complicated when tidal currents are present that there is often considerable doubt as to the validity of temperature, salinity or density sections constructed from isolated sets of observations. Repeated observations in a region will give certain consistent results which can be separated from the temporary variations, but it is not always possible to obtain successive sets of observations at each station. The writer has attempted to minimize the tidal variations by taking simultaneous sections from two boats or else by comparing sections taken on the same phase of successive tides.

The constancy of the salinity and temperature of a mass of water in the sea is effectively utilized in the T-S diagram method of tracing the circulation. Temperature and salinity are used as coordinates and the depth is noted in figures beside the plotted point. Points representing conditions at various depths for one station are joined by a smooth curve. The use of these diagrams is well illustrated by Jacobsen (1929) in his analysis of the movements of North Atlantic waters. They are most valuable when the waters of a region are composed of varying proportions of two or more source waters of definite salinity and temperature. The bay of Fundy has no other sources than fresh water and the waters from the gulf of Maine. As the latter are continuously variable between limits rather than composed of several different types the T-S diagram is not very fruitful for the bay in general, but there are a number of local cases in which it gives valuable information as to the origin of the water. An improvement to the diagram is to draw on it a set of curves for equal densities. The vertical distribution of temperature salinity and density can then be shown simultaneously by a single curve for each station.

The last and most formal physical method of attack on the problem is the calculation for each station of the dynamic height of water above the bottom or above some level at which the water movements are negligible. A dynamic topographic chart is plotted in which the contours are dynamic isobaths. The water flows along the contours and the current strength is proportional to the gradient which is calculable from the distance between the isobaths. In shallow seas such as the gulf of Maine and the bay of Fundy it is necessary to calculate the gradient between pairs of adjacent stations and to determine the dynamic heights relative to some one chosen station. When the two adjacent stations are of different depths the water between them and below the bottom level of

the shallower station will in general be in motion and the dynamic gradient at the surface can only be obtained by applying an approximate correction for the gradient due to this moving bottom water. In the bay of Fundy the change in depth between adjacent stations is often a large fraction of the depth, with the consequence that the uncertain gradient due to the bottom current is nearly as large as the gradient obtained from the difference in weight of the upper waters. A further source of uncertainty lies in the fact that owing to the strong tidal currents throughout the bay it is unsafe to lower the water bottles very close to the bottom and as a result the true bottom densities are not obtained. In future work it would be advisable to use a heavily constructed water bottle of the insulating type which could be lowered right on to the bottom with safety.

In a preliminary study of large regions the occurrence and distribution of plankton often furnishes the first indication of the circulation in the region. On the other hand when the water in a region is as nearly homogeneous in character as in the bay of Fundy the indications of one species contradict those of another species and it seems that there are too many factors affecting their distribution for plankton to be of much use in determining the residual currents. The phytoplankton is so much more at the mercy of the water movements than the zooplankton that it does give considerable confirmatory evidence about the circulation in restricted regions. But even with the phytoplankton the response to light must constantly be borne in mind so that changes in distribution shall not be attributed solely to the movement of the water. It is fortunate that in this investigation the phytoplankton studies were carried out during the same period as the hydrographic measurements, for these two branches of the investigations were most helpful to each other.

PART II. ANALYSIS OF OBSERVATIONS

1. ARRANGEMENT AND NOMENCLATURE

The observations obtained in the bay of Fundy during 1932 were not complete enough for a presentation of temperature and salinity conditions in successive months over the whole area. It must be remembered that the main object of the investigation was not the oceanography of the bay of Fundy in general, but the particular part played by the Quoddy mixing mechanism. It seems best to present the observations in the order in which they were obtained and to discuss important local features as they become apparent. It will be found that vertical sections are used more commonly than horizontal ones, for owing to the low stability of the region the movement of any particular body of water is seldom restricted to a horizontal plane. For the same reson it is better to study the distribution of density, salinity and temperature together rather than separately.

A key chart to the hydrographic stations occupied is given in figure 1. The stations are arranged in lines running from one prominent shore point to another, or else running out to sea in a straight line from a shore point. All stations on one line are numbered outward from the shore and are prefixed by

one or two letters which designate the shore point from which the line starts. Thus S3 is the third station from shore on the line extending out to sea from Swallow Tail lighthouse. Stations on the two longest lines crossing the bay are given numbers without any prefix since they are too far from shore to be referred to it. Single stations in narrow passages are denoted by two letters, chosen from the names of the places used to locate them, as for example S-H which is a station between Spruce island and Head harbour. This system of nomenclature is particularly suitable for a region of the size of the bay of Fundy since the name of each station conveys sufficient information for any one familiar with the region to locate it mentally without having to refer each time to a key chart. Since observations are often made at the same station at frequent intervals it is necessary to specify the date and time rather than a cruise number. On the other hand the plankton stations were taken on monthly cruises extending over a much larger area, so that a different system of nomenclature was more suitable. Plankton station 25.05 means station 5, as found from a key chart, taken on cruise 25. It should be pointed out that owing to the variety of work carried out at the plankton stations the hydrographic observations were usually taken in two series, as much as a hour apart, with a consequent lack of simultaneity and uncertainty of position. At the hydrographic stations on the other hand every effort was made to have the position exact and to complete the observations in a minimum time, about 25 minutes at the deepest stations. For qualitative purposes however the hydrographic data from the plankton stations is a valuable addition to that obtained at the purely hydrographic stations.

In order to clarify references to the various regions in the bay of Fundy the following nomenclature will be used in all reports made on the investigations for the International Passamaquoddy Fisheries Commission. The **QUODDY REGION** comprises the whole body of water which lies within a line drawn from West Quoddy Head to the northern extremity of Grand Manan island and on to point Lepreau. Further subdivisions of the Quoddy Region are: **Passamaquoddy bay,** or the inner bay, lying inside of Deer island and not including any part of the passages which connect it to the outside waters; **Cobscook bay,** lying within a line drawn from Eastport to Lubec; and the **Quoddy passages,** which include the entrance passages to these two bays together with the waters among the many small islands outside Deer island as far as a line drawn from East Quoddy head (or Head Harbour light) to Bliss island; and finally the **Outer Quoddy region** which is that part of the Quoddy region lying outside of this line and within the line from West Quoddy head to Grand Manan and on to point Lepreau. **GRAND MANAN CHANNEL** is the body of water between Grand Manan island and the coast of Maine extending from the Quoddy region to a line drawn from Machias bay, Maine, to Machias Seal island and up to Southwest head, Grand Manan. The **BAY OF FUNDY** extends in a northeasterly direction from the gulf of Maine and the position of any line chosen to divide the two regions for purposes of reference must be somewhat arbitrary. We shall consider the boundary of the bay of Fundy to extend from Machias bay, Maine, to Grand Manan bank and across to Brier island, N.S. The name bay of Fundy will be used to represent the entire bay in distinction to the gulf of Maine, and

also the major portion of the bay excluding the Quoddy region and Grand Manan channel in distinction to either or both of these local areas.

2. Conditions in Winter and early Spring

During the winter of 1931-32 observations were taken at stations in Passamaquoddy bay, the Outer Quoddy region and the Fundy deep. The salinity values were destroyed by fire but the temperatures are given on page 196, and in the hydrographic tables. In the Fundy deep the lowest surface temperature was probably about 2°, early in March, and at 50 metres 2.7° in the middle of March. In Passamaquoddy bay temperatures are lower, although the tidal
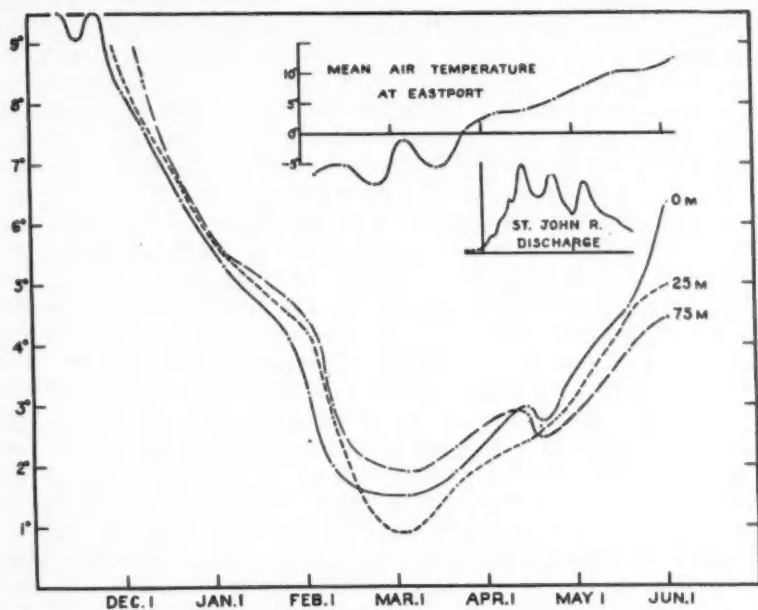
FIGURE 8. Water temperature at station 5, Outer Quoddy region, with contemporary air temperature at Eastport and fresh water discharge at Saint John.

stirring and admixture of deep water from outside prevents the temperature falling as low as one might expect for such a land locked basin. Early in February the formation of an ice sheet in the harbour prevented the use of the boat for a time, but from the observations taken it would appear that the temperature difference of about 1° between surface and 25 metres persists even into February. On March 1 this difference had disappeared. It is noteworthy that in the Fundy deep the water below 10 metres had risen from 2.9° to 3.7° between March 5 and April 21. From the air temperatures at Eastport, Maine, during this period (see fig. 8) it does not seem possible that this was due to direct solar warming alone, especially as the water from the coastal regions is still colder.

5

The rise in temperature must be due to the inflow of warmer water from the gulf of Maine. The progress of this water from the Eastern channel of the gulf of Maine is well shown by Bigelow (1927, figs. 12, 24, and 192) in his temperature charts for 40 metres.

In the Outer Quoddy region temperatures show the influence of the nearby bays and of water from the Saint John region. Figure 8 shows the contemporary progress of the water temperature at sta. 5 (Quoddy region, lat. 44° 57′, long. 66° 49′), the air temperature at Eastport, Maine, and the volume of the Saint John river discharge. At the end of February the water in Passamaquoddy and Cobscook bays is undergoing severe cooling, especially at the intertidal zone along the shore. Owing to the strong tidal movements this chilled marginal water does not remain near shore but is rapidly distributed throughout the whole volume of water in the bays. This tidal interchange is also the reason why the water does not reach as low a temperature as in bays much farther south, as for example in Cape Cod bay. When the chilled water emerges from the bays into the outer Quoddy region it finds its density level below the surface. At sta. 5 its influence on the 25 metre thermogram is most noticeable around March 1 when the temperature at that level is the same as within the bay, while at the surface and below 40 metres it is more than 0.6° higher. The relative density of the water emerging from the Quoddy passages at any time is dependent on the amount of fresh water inflow to the bays and on the supply of heavy bottom water to the mixing mechanism of the passages. In the earlier part of the winter, overturning has almost equalized the density of the outer Quoddy waters from surface to bottom, but the rivers are still supplying fresh water to the bays in sufficient quantity to cause the mixed water from the passages to be lighter than any water outside, so that the outflow will be mainly in the surface layers. During February, however, the river discharge falls to its minimum for the year and there is not sufficient fresh water to make up for the increase in density due to the extra cooling, with the result that at sta. 5 the outflow is found at the 25 metre level rather than at the surface. Since the reduction of the fresh water is itself due to the low air temperatures the two factors affecting the density work simultaneously to shift the level of the outflow downward and to cool the 25 metre water rapidly during February. In 1932 the river outflow in March remained as small as in February (see fig. 5), though this is not always the case, and it was not until late April that the arrival of the freshet water together with the vernal warming restored the vertical temperature distribution curve at sta. 5 to its normal summer shape.

3. April Conditions; the St. John River and the Spring Freshets

The variation in the time of occurrence and volume of the spring freshets has already been discussed (Part 1, sect. 3). In 1932 the Saint John freshets began about April 2 and reached a maximum on April 14 and 15. This event marks the beginning of rapid changes in the oceanography of the bay and constitutes one of the greatest single factors in its subsequent development. Before tracing the Saint John water we must examine the unusual conditions in the mouth of the river produced by the so called "reversing falls."

The Saint John river empties into the sea from a large fresh water basin through a rocky gorge about 4 miles (6.5 km.) in length. About half way along this gorge there is a constriction which reduces its width to less than 100 yards (90 m.). With the inner basin acting as a reservoir the water cannot flow through the channel rapidly enough for the level inside to keep pace with the tidal level outside. For a period at low water there is a fall of several feet at the water passes outward through the constriction, while on the inward flow as high water there is a somewhat smaller fall in the opposite direction. During great freshets the height of the river may be such that the inward fall does not occur. Between the periods when the water falls in opposite directions there is a time when the current slackens and turns and for a period of about half an hour before and after the time of slack water navigation is quite practicable. This slack water normally occurs at the end of the inward run 2 hours, 25 min. after high water, and at the end of the outward run 3 hours 50 min. after low water. While this phenomenon of a reversing falls is not quite as spectacular as its name might suggest it rarely occurs on such a scale in a natural water-course and has consequently become widely known. From the oceanographic viewpoint however it is interesting because the estuarial conditions here are unique and have a profound influence on the western part of the bay of Fundy. In most estuaries where the tidal range is large (Severn estuary, Gibson 1933; Penobscot bay, Seiwell 1932) the change in salinity from surface to bottom is not as great as from station to station and on reaching the sea the water is not markedly stratified. At Saint John the waters of intermediate salinity flow outward in a surface layer about 5 metres thick, within which the density gradient is steep, while below this the water is almost undiluted and homogeneous Fundy water. It is well known that any such mixing mechanism which produces a surface outflow of water of intermediate salinity must consume salt bottom water, which therefore flows in towards the mixing region. Navigators are warned that within Partridge island the outward surface flow may still be evident after half-tide rising while at a depth varying with the stage of the tide a strong inward current may exist. The sharp change in density gradient which occurs at a depth somewhere between 5 and 10 metres may be found not only just outside Saint John harbour, but even 40 miles (74 km.) away off Grand Manan island (see fig. 9). The effect of this surface outflow is described in the next section, and a discussion of its remarkable resistance to vertical mixing will be found in Part III, section 1.

The spring freshets may be accompanied by another seasonal event, the occurrence of the maximum spring tides. These are produced when the moon is at perigee, at the same time as it is new or full. These high tides usually occur in the spring months and again at the end of the summer, but the dates are very variable from year to year. In 1932 maximum spring tides were on April 20-23, just after the commencement of the freshets. Observations were taken at sta. 5 on April 19 and 20 and again on April 25 and 26, before and after the spring tides, and at the mid-point of the northern end of Grand Manan channel on April 22 during the spring tides. The outstanding feature of these observations is the variability of conditions at sta. 5, both with the stage of tide and with the wind.

By comparing the averages for each depth of all observations on the 19th and 20th with those on the 25th and 26th it appears that after the strong tides there is an increase of salinity at all depths with a decrease of stratification. It seems that both at high water and at low water a strong south wind freshens the water at all depths, but especially at the surface (see L.W. on April 19 and H.W. on April 25). There are two possible sources for this fresher water, the outflow from the Quoddy passages which may normally pass to the west and south of sta. 5, and the channel between Grand Manan and the Wolves. The former is unlikely because the surface water at the Grand Manan channel station on April 22 at the end of the ebb and with a light NW wind is not as fresh as the south wind surface water at sta. 5. On the other hand the observations taken on April 21 at plankton sta. 6, which is just north of Grand Manan island, show that the water there is much colder at all depths and fresher down to about 30 metres than at sta. 5. The lowest temperature at sta. 6 is 1.4°C. at the 25 metre level. This cold water may be partly the Quoddy outflow at the end of February (see sect. 2) which has slowly worked its way to the north of Grand Manan, getting slightly warmer during March, but protected by the stable surface layers after the commencement of the freshets. For the same reason the coldest water found in the bay of Fundy during April is the sub-surface water between Saint John and Lepreau. On April 18 the water at 10 metres depth off Lepreau was just below zero degrees in temperature. Even before the freshets in April the outflow from the Saint John river was sufficient to produce a surface layer as far as Lepreau which was stable enough to protect the water beneath from the vernal warming.

The observations at the northern end of Grand Manan channel on April 22, during maximum tides, show that the dominant drift through the channel is towards the Quoddy region. At high water the water at all depths below 10 metres was completely homogeneous. At low water it is stratified, but below 10 metres much salter and slightly colder than at high water. This means that though some Quoddy water may enter the channel during the ebb tide it is completely driven out by the end of the succeeding flood tide, since at high water the water shows no trace of mixture with Quoddy water. During the ebb tide some of the deeper water which enters the channel must have come around the northern end of the island, for below 10 metres it is more saline than any sta. 5 water, but intermediate between the homogeneous channel water and the sta. 6 water below 35 metres. The slightly fresher surface water may have come from sta. 5 or else directly from the Lubec channel.

To summarize the conditions in the Outer Quoddy region at this time we can say that it is the meeting place of many waters, where the variable conditions of wind, tide and freshets preclude any constant circulation. If water enters the region from the Quoddy passages, from Grand Manan channel and occasionally at some level from sta. 6, it must obviously flow outward somewhere. It is difficult to say what the effect of the prevailing NW wind would be, except that it would tend to drive the surface water out of the region. We have no observations at this time from the shallow channel north of the Wolves and it is possible that there is a clockwise circulation around the Wolves. This would agree with the movement of the Saint John outflow, for the Outer Quoddy region would then
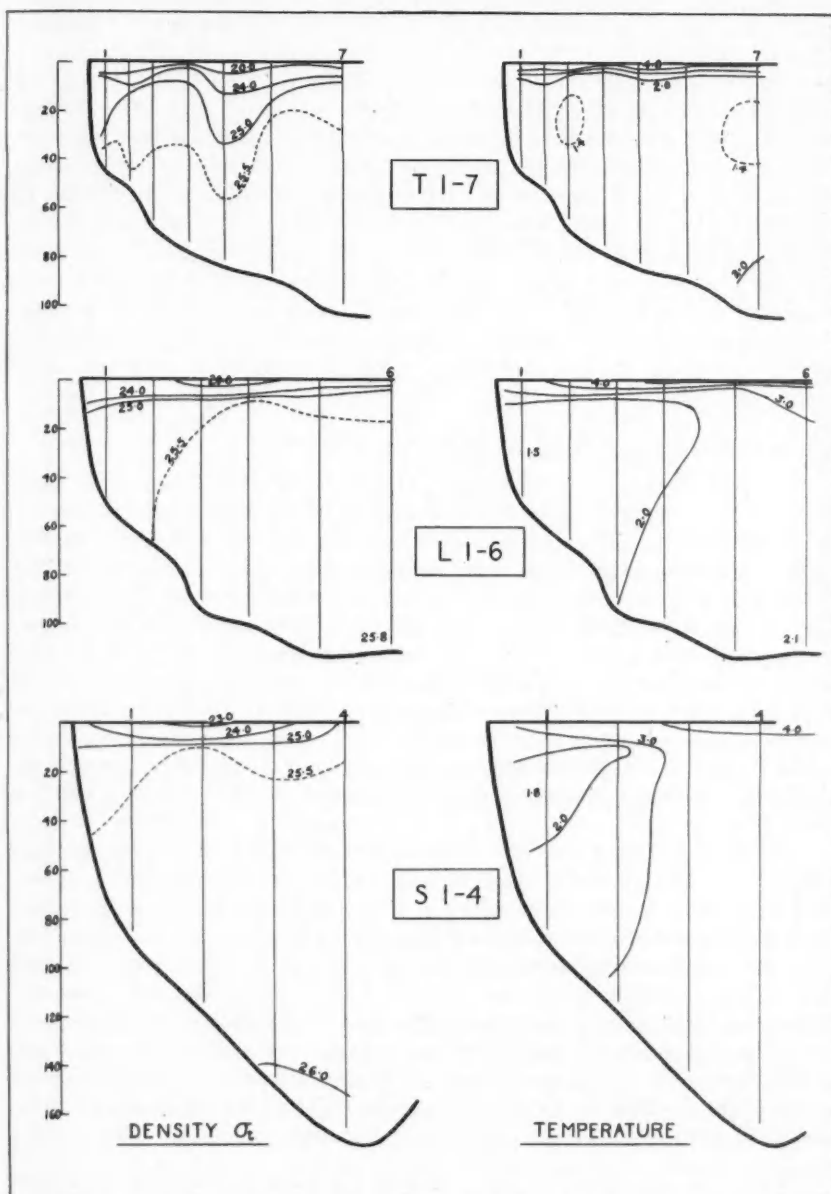
FIGURE 9. σ_t (density) and temperature sections across the Saint John outflow, April 30-May 4, 1932.

contain a large residual eddy generated by the residual surface drift sweeping past from Lepreau to the east of Grand Manan. One has constantly to remember that any residual current in the bay of Fundy is a slow movement composed of the differences between successive tidal displacements. It is bold to speak of an. eddy when referring to residual movements of a circulatory nature but the justification is that the differences, as well as the tidal currents themselves, must fulfil the laws of continuity. Consequently a residual current moving past an abrupt opening in the coast line may be said to generate a residual eddy within the opening, provided we understand that the detailed motion in this eddy is not a simple circulation. If future observations show that water does not leave the region by means of such a clockwise eddy around the Wolves then the only other possibility is that it passes out between the Wolves and Grand Manan as a subsurface layer, and that its rate of progress is so slow that water which originated in the passages at the end of February is found north of Grand Manan at 25 metres on April 21.

4. THE SAINT JOHN OUTFLOW, APRIL 30-MAY 4

In 1932, at the end of April, the Saint John freshets had been running at full strength for over three weeks and it seemed to be the most favourable time to study the outflow. The stations chosen were located 3 miles (5.6 km.) apart or less on lines running out to sea from Tiner point, point Lepreau and Swallow Tail, so as to give three vertical sections across the probable course of the outflow. Each section took about $4\frac{1}{2}$ hours and was made between half ebb and the succeeding half flood, so that they may be regarded as low water sections. Figure 9 shows the densities and temperatures for each section, while figure 10 shows the horizontal distribution of salinity at the surface. Salinity sections are not shown as they correspond closely to the density sections, owing to the small temperature range. The actual salinity values can be found from the tables, but roughly the isoline for $\sigma_t = 24.0$ corresponds to an isohaline for $S = 30.1^0/_{00}$ and $\sigma_t = 25.0$ to $S = 31.3^0/_{00}$.*

We have seen that the Saint John outflow emerges from the harbour as a surface layer 5 to 10 metres thick with a very strong density gradient, flowing over water which is almost homogeneous. The subsequent history of this surface layer may be traced in the sections of figure 9. Between Saint John and Tiner point the most violent adjustments are being made, for the velocity of the surface flow is being checked by friction with the homogeneous tidal water beneath. Moreover, since Tiner point is only 9 miles (16.7 km.) from Saint John, the river outflow is still somewhat intermittent and has not yet had time to spread into an even layer. In each of the sections the whole of the deeper water lies between $\sigma_t = 25.0$ and $\sigma_t = 26.0$, so we may consider $\sigma_t = 25.0$ as the dividing surface between the stratified layer and the deeper homogeneous water. The velocity

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*NOTE.—The word "isoline' is used in this paper as a general word referring inclusively to isotherms, isohalines and isopycnals. In spite of being a hybrid word its simplicity and obvious meaning seem to justify its use in preference to the word "isogram", which suggests a line traced by a recording instrument rather than one drawn through points where the interpolated values are equal.

gradient across the $\sigma_t = 25$ surface causes vertical mixing and the mixing increases the volume of stratified water at the expense of its stability. Since the quantity of water heavier than $\sigma_t = 25$ is very large there is no noticeable change in it, but the surface water becomes progressively heavier. Comparing the three sections in order we see that σ_t for the lightest surface water increases from 16 off Tiner to 23 off Swallow Tail. One would expect the $\sigma_t = 25$ surface to get deeper along the line of flow, but the horizontal spreading of the surface layer compensates for its tendency to thicken with the result that the Lepreau and Swallow Tail sections both show the $\sigma_t = 25$ surface at the same depth, about 10 metres. Beyond the Swallow Tail section the diminishing vertical density gradient in the
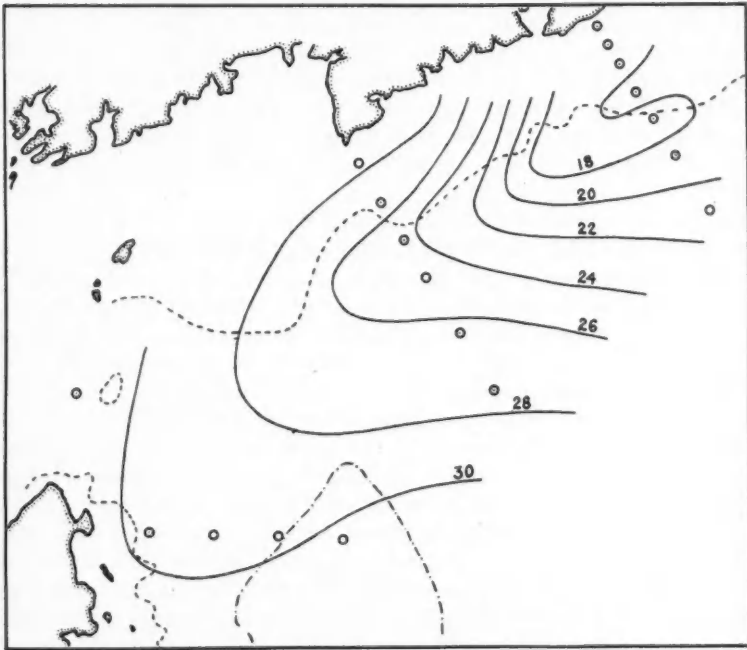
FIGURE 10. Surface salinity, Saint John to Grand Manan, April 30-May 4, 1932.

surface layer is rapidly destroyed and its existence as a distinct layer comes to an end. The sections do not go far enough towards the Nova Scotian shore to show the limits of the surface layer in that direction but it seems probable from observations later in the month that there is a spreading of the light surface layer across the bay towards Digby as well as along the eastern slope of Grand Manan. However, the sections do cover the region where the surface layer has the greatest stability and we may now consider the effect of this layer on the temperature of the water beneath it.

During the period of vernal warming heat is transferred downward through the water mainly by vertical mixing, for nearly all of the direct solar radiat ion

is absorbed in the first 10 metres (see Bigelow 1927, pp. 674-680). If the surface layers are so stable that they are practically impenetrable to the eddies which effect vertical mixing, then there will be a negligible transfer of heat downward. Most of the heat absorbed will remain at the surface, where it is utilized in evaporation and in raising the temperature until thermal equilibrium with the air is reached. The average surface temperature along the Tiner and Lepreau sections is 4.6°, while the mean air temperature at this time is only about 7°. In
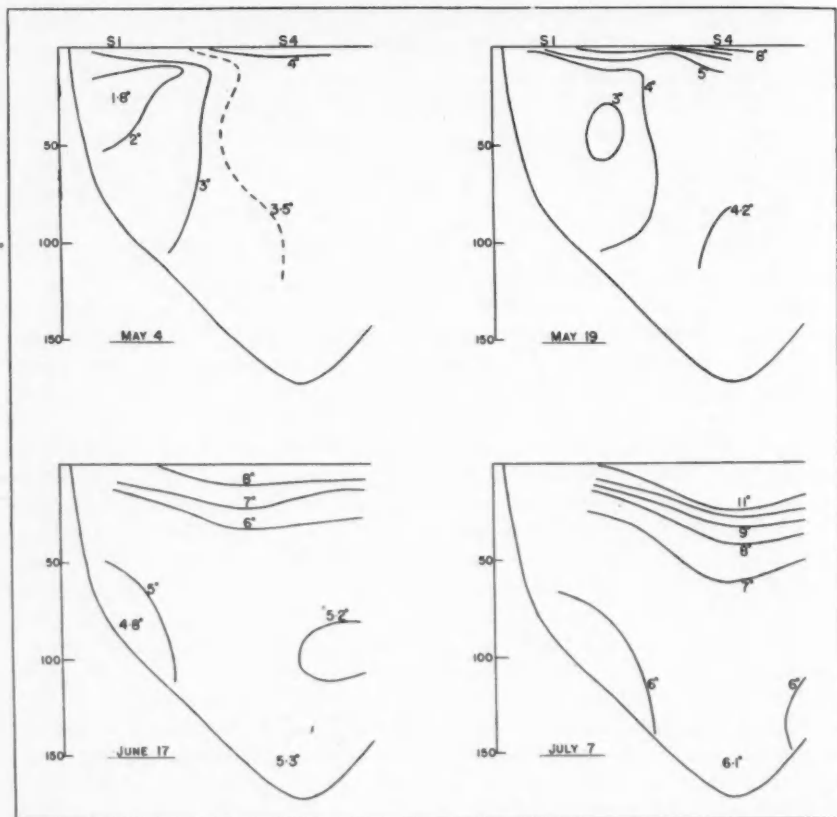
FIGURE 11. Vertical temperature sections, Swallow Tail, May, June, July, 1932.

contrast to the high surface temperatures we find that the insulating effect of the surface layer has preserved a body of water below the 10 metre level at a temperature between 1° and 2° (see temperature sections, fig. 9). This winter-cooled water, protected from vernal warming, is now the coldest body of water to be found within the bay of Fundy or the gulf of Maine. Off Tiner it extends beyond the end of the section, while at Lepreau and Swallow Tail it is found for about 10 miles (18 km.) off shore. The distribution of this cold water corres-

ponds with that of water shoaler than 100 metres which lies below the stable surface layer. Whether it is continuous from Lepreau to Swallow Tail across the deep channel between them is uncertain, but from the similar characteristics of the water it seems probable. Since this water remains colder than the rest of the bay until well on in June it may be of importance biologically as well as physically. Figure 11 shows the temperature distribution in the Swallow Tail section on May 4, May 19, June 17 and July 7. As the season progresses the coldest water is found surviving at increasing depths since the upper levels warm most rapidly. The normal condition in the gulf of Maine is to have a minimum temperature at the lowest level to which the winter overturning has penetrated, usually about 100 metres on the coastal slope (Bigelow 1927, fig. 37). This level remains the coldest throughout the summer. The cold Fundy water which we are considering is a more local phenomenon and occurs at a higher level, about 25 metres at the beginning of May. Its proximity to the surface and the temperature range existing within a few metres may be of considerable importance to certain species of plankton. On the other hand the turbidity of the stable surface layer reduces the light intensity to a value found at greater depths elsewhere.

Between Saint John and point Lepreau the surface layer moves parallel to the coast with a velocity which Mavor (1922) estimates from drift bottle returns as 4 to 5 sea miles per day, or about 10 cm./sec., in August. We shall presently show from the hydrographic data that the maximum velocity on May 3 was about 30 cm./sec. Since this is quite an appreciable velocity we would expect the current to continue following the shore line on its right and flow into the Quoddy region, but it appears that the gravity forces tending to drive surface water away from the region are strong enough under normal conditions to resist the dynamic forces acting on the current The result is that it is forced offshore at Lepreau and flows towards the east side of Grand Manan. The balance between the Archimedean or gravity forces and the dynamic forces will be greatly influenced by the wind. A west or northwest wind will help to keep the Saint John current out of the Quoddy region while a south or southeast wind will tend to drive it inwards. A wind from the southwest, which is the prevailing direction in summer, will gradually push back the surface layer until its dynamic height is increased sufficiently for it to overcome resistance and spread to both sides. A measure of the gravity forces at any time may be obtained by comparing the dynamic heights of the water between the sea surface and the isobaric surface for 75 decibars (metres) at station 5 in the Quoddy region and at the station off Lepreau where the freshest surface water lies. This height D may be computed from the hydrographic data for

$$D = \int \alpha . dp = \Sigma \bar{a} . \Delta p = \Sigma \bar{a} . \Delta_z \text{ dynamic metres,}$$

where α =specific volume in situ and z =depth in metres

$\bar{a}$ =mean specific volume between two observed depths whose vertical distance apart is Δz.

The following table gives the heights for station 5 at various times with different wind conditions and the heights at L3 and L4 on the Lepreau section where the

freshest water lay on May 3. In the table 73 metres has been deducted from each height and the decimal moved two places so that the figures are now dynamic cm.

Date	Tide	Wind	Sta. 5	L3	L4
April 19	L.W.	Strong S	20.00 cm.		
" 20	L.W.	Light NW	16.57		
Maximum spring tides occurred on April 20-23					
" 25	L.W.	Light NW	15.27		
" 26	L.W.	. . . .	16.25		
May 3	1-2 hrs. flood	Fresh NW	. . . . .	16.13	14.82
May 31	Various times	SW to NW	16.3-16.8		
June 2	L.W.	S	17.3		

The table shows that the Quoddy region water at station 5 is in general dynamically higher than the water of the Saint John current. Its height is increased by a south wind and decreased by spring tides. The latter increase the rate of horizontal interchange and thereby increase the average density in regions where it is normally low. To say that station 5 is dynamically higher than the surrounding region merely means that the water there is on the average lighter than elsewhere. Why this should be so is not obvious, for it certainly is not necessarily fresher. Indeed if we calculate the mean salinity for station 5 on April 26 and for L3 on May 3 we get $31.48^0/_{00}$ and $31.42^0/_{00}$ respectively, so that the latter is fresher. But the water at station 5 is lighter because, surface temperatures notwithstanding, its average temperature is higher. The water below the Saint John current has remained low in temperature, insulated by the stable surface layers; while the water of the Quoddy region, stirred by the mixing mechanism of the passages, has been absorbing heat throughout its depth. Any serious change in the efficiency of this mixing mechanism brought about by the construction of dams for tidal power purposes might cause important changes in the residual currents at this time of the year. With an increase of stratification there would be slower heat absorption and a decrease in the dynamic height. The Saint John current might then sweep into the Outer Quoddy region and cold subsurface water would no longer be found on the eastern slope of Grand Manan.

We may use the dynamic heights obtained for stations L3 and L4 to determine the maximum surface velocity of the Saint John current, since these two stations lie on a section crossing the current at right angles and the median line of the freshest surface water passes between them. The latitude is 45° and the stations are 3.7 kilometres apart, hence we have

$$v_0 - v_{75} = \frac{(D_3 - D_4) \cdot 10^5}{(14.58 \sin 45°)L} \text{ cm./sec.} = \frac{1.31 \times 10^5}{10.3 \times 3.7} = 34 \text{ cm./sec.}$$

Since from figure 9 the water at 75 metres is practically homogeneous between L3 and L4 there are no solenoids at this depth, so that $v_{75} = 0$ and the surface

velocity is 34 cm./sec. (0.7 knots) away from Saint John. This is the velocity of the residual current exclusive of the tidal movement. Actually the observations were made between one and two hours flood when the tide was flowing towards Saint John. From the hydrographic data it is possible to calculate the velocities across the section at all points and thus obtain a figure for the total transport of water across it at different depths.

5. The Central Eddy and the Grand Manan Shoals (May 18-19)

On May 18 and 19 three sections were made across the coastal slope on the east side of Grand Manan island. The object of these was primarily to determine the extent of influence of the shoals and rips as a mixing mechanism, and secondly to observe their effect on the stable surface layer of water which is produced by the Saint John current. The Swallow Tail section was placed as before while the two new ones were on either side of the series of shoals running out from White Head island to the Old Proprietor shoal. Hydrographic observations in this region are somewhat hazardous if the boat's engines are not reliable, because the tidal velocity over the shoals is from four to six knots and the bottom is uneven and rocky. Furthermore the rapid drifting of the boat makes it unsafe to lower the water bottles close to bottom. It would have been preferable to obtain these sections on the ebb tide, for comparison with the previous low water observations, but favourable weather conditions and a suitable opportunity occurred together only on the flood tide. The Proprietor section was started about an hour after low water and the White Head section finished by the succeeding high water, so that both sections were completed in the same flood tide. The Swallow Tail section was made at the end of the next flood tide. For comparison with figure 10 the surface salinity distribution is shown in figure 12. To aid in drawing the isohalines the surface salinites at plankton stations in neighbouring regions on May 22-24 are used.

By calculating the dynamic heights of the water above the 100 decibar surface for stations S2, S3 and S4 we obtain 97.51481, 97.50144 and 97.51428 dyn. metres respectively. From these we obtain the components of surface velocity at right angles to the section as 23.4 cm./sec. south between S2 and S3 and 22.4 cm./sec. north between S3 and S4. The distribution of salinity in figure 12, together with these velocity determinations, shows that there is a counter-clockwise circulation about station S3. It will be seen from subsequent data (see fig. 15, sta. 17) that this is a permanent feature of the water movements in the bay and we shall refer to it as the central eddy. The light water supplied to it by the Saint John current is continuously being used up all around its periphery in vertical mixing, so that as we move away from it the surface salinity increases. This absorption of the surface water by mixing is most intense among the islands and shoals of Grand Manan, and consequently the $30.5^0/_{00}$ isohaline in figure 12 is drawn in towards this region. But the quantity of surface water absorbed from the central eddy by the Grand Manan shoals is only a small part of the total amount absorbed all around its long periphery. Here we have another example of a general observation on the behaviour of banks and shoals (cf. Part I, sect. 4), namely, that in spite of the very noticeable turmoil and mixing

the bank water seems to be confined to the bank and is not found in any unusual quantity a short distance away. In figure 13 the density isolines are shown for the Proprietor and White Head sections. There is a striking difference in stratification between the two sections, although they are only about eight miles (15 km.) apart, and there does not seem to be any accumulation in the W H section
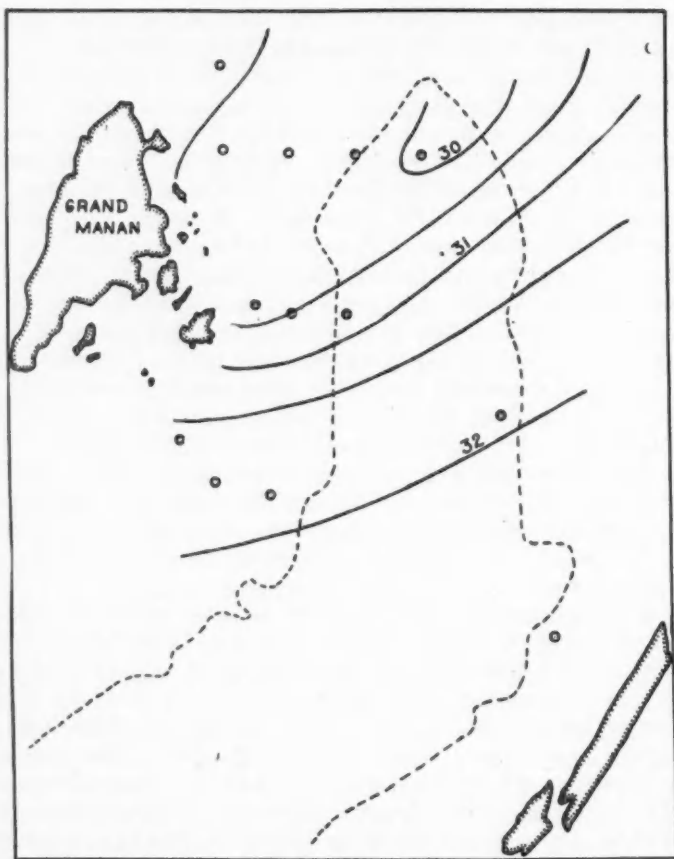
FIGURE 12. Surface salinity, May 18, 1932.

of the almost homogeneous water of the P section. Thus the efficient vertical mixing in the shallow region east and southeast of Grand Manan affects the shape of the pool of light surface water but it does not play a major part in the consumption of this water. Nor is the quantity of intermediate mixed water which leaves the region very large, for it cannot be traced with any certainty.

6. Grand Manan Channel (June 13); Homogeneous Water

One June 13 two pairs of simultaneous sections were made across each end of Grand Manan channel, at low water and at high water. The northern section lies between West Quoddy head and Indian beach while the southern section lies between Moose cove and South West head. The density sections are shown in figure 14. The Quoddy head section is much more stratified at low water than at high water and shows an intrusion of Quoddy water into the channel at all depths. Similarly the Moose cove section shows an intrusion of slightly stratified surface water from the south at high water. The region to the south of the channel is shallower and more effectively mixed than the Outer Quoddy region. The hydrographic observations suggest that the water in the channel and in the
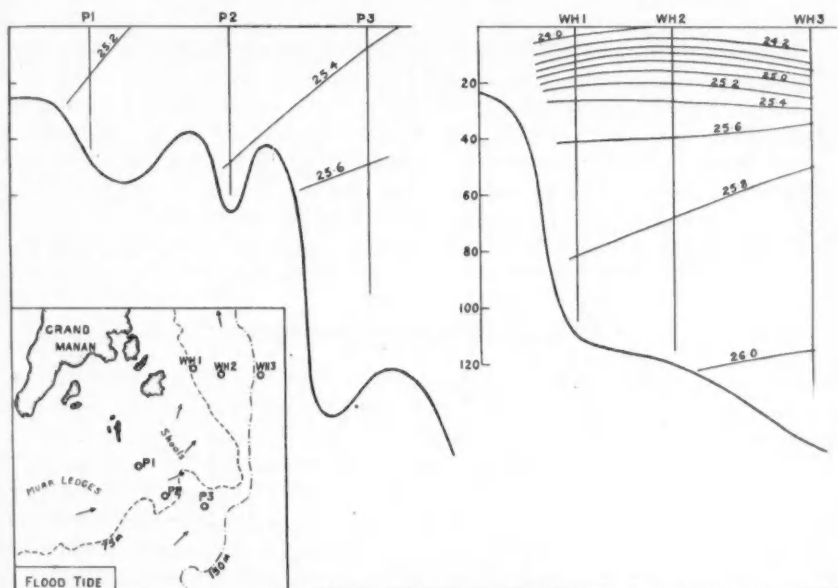
Figure 13. Vertical density sections off Grand Manan; values for σ_t, May 18, 1932.

region just south of it may be stagnant as far as residual currents are concerned, even though the tidal currents are obviously strong. A further examination of the data with this possibility in mind gives interesting results. Consider the observations at station MC3 at high water. The density figures show a certain amount of stratification, especially in the top ten metres, but we find that this is due entirely to the temperature gradient, for the salinity is constant from surface to bottom. What is the history of water with such characteristics? If we take sea-water of salinity $32^0/_{00}$ and heat it from $5°$ to $7°$, the water will expand while the mass of the salt remains the same, thus reducing the salinity to $31.99^0/_{00}$ and the density from $\sigma_t = 25.32$ to $\sigma_t = 25.08$. Heating has therefore produced a corresponding change in density without appreciably altering the salinity. It
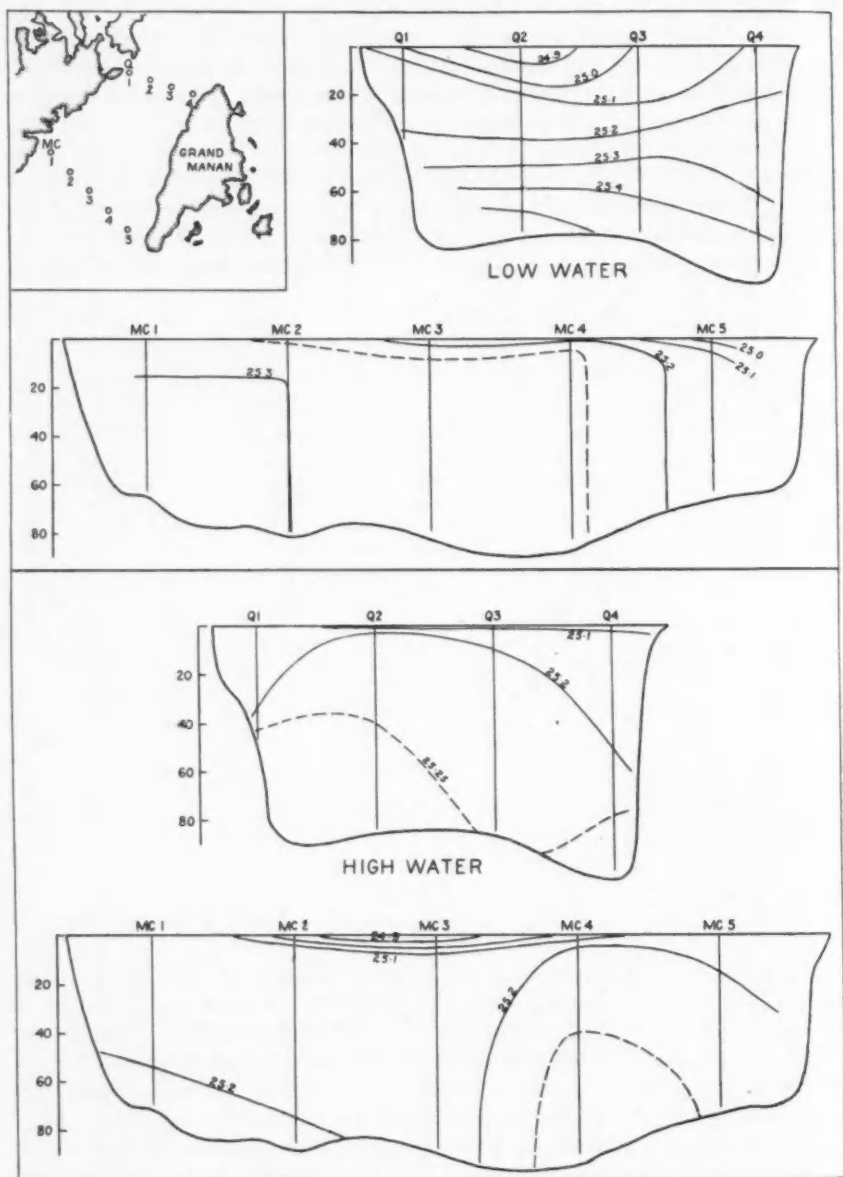
FIGURE 14. σ_t (density) sections, Grand Manan channel, June 13, 1932.

would appear that this water at station MC3 has at some previous time been thoroughly mixed and has since been undergoing vernal warming without further mixing.   The latter condition will be met if the tidal velocities remain constant down to the depth at which stratification due to temperature is appreciable, in this case about 15 metres.   Now the depth of the channel is remarkably uniform and the sides are smooth, so that the motion of the water is probably more nearly irrotational than usual.   The velocity gradient will in such a case be very small or even zero for some distance below the surface and then increase rapidly near the bottom (Powell 1925).

Having shown how such temperature stratified water of constant salinity can exist in the channel we can now draw the conclusion that there is very little horizontal interchange at this time with the more stratified water of the Outer Quoddy region.   The water to the south is already fairly homogeneous owing to continuous tidal mixing.   Hence the constant salinity water in the channel has probably come in from the south but has remained long enough to acquire a temperature gradient of 2.4° in 10 metres.   Therefore the residual current is directed northward but is small.   During the summer months it may be largely due to the prevailing SW winds which would help to propel it in this direction. The consideration of conditions in Grand Manan channel has led to the estab- lishment of certain general principles with regard to bodies of homogeneous water. These principles are applicable to coastal waters generally and are therefore presented in Part III, section 2.

7. June Hydrographic Survey of Bay of Fundy

By using both boats the whole bay of Fundy was covered by transverse hydrographic sections between June 15 and 18.   The most important features of this survey have been presented in figures 15-18, while further information may be obtained from the tables of observations.   Figures 15 and 16 show the distribution of density throughout the bay.   The mixing effect of bottom friction is particularly noticeable in these sections.   The density isolines, which are normally horizontal, turn downward as they come within 20 to 50 metres of a shoaling bottom, the distance depending on the nature of the currents.   If the bottom rises steeply the area of mixing is small and there is much less effect on the isolines.   Thus in the Grand Manan to Digby section the lines turn down- ward to the gradually shelving bottom on the Digby side, but meet the steep bottom slope at Grand Manan without change.   This condition is reversed in the southernmost section, where the bottom off Brier island slopes steeply while on the Maine side the bottom rises gradually above 100 metres.   Near the head of the bay of Fundy between Found head and Margaretville the average depth is only 50 metres, and the tidal currents are very strong, with the result that the density isolines are actually vertical.   Why the water on the New Brunswick side should be lighter than on the Nova Scotian side is not clear, for there is con- siderably more fresh water running into Minas basin than into Chignecto bay (see fig. 3).   Possibly the light water from Minas basin has already been driven westward above this section.   In such homogeneous water wind effects must also
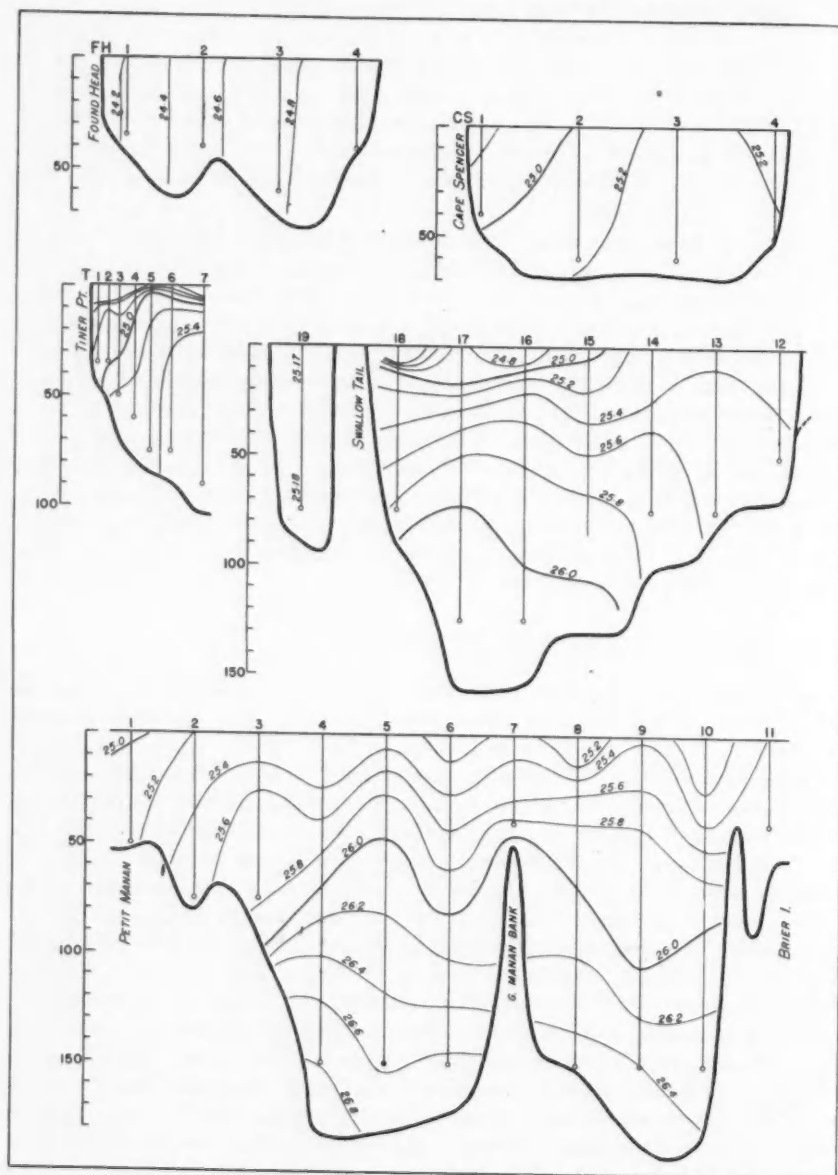
FIGURE 15. Transverse σ_t (density) sections, bay of Fundy, June 15-18, 1932.

be important, but there are not enough data at hand to study this interesting region in any detail.

The effect on the isolines of a gradually shoaling bottom is further demonstrated by the longitudinal sections of the bay in figure 16. The progressive lightening of the water at any level as the head of the bay is approached is slightly modified near the surface by the Saint John outflow and by the cyclonic circulation around station 17 (approximately the same as station S3; see sect. 5). This progressive lightening shown by the slope of the surfaces of equal density is indicative of the fundamental movement of light water from the bay of Fundy towards the gulf of Maine. Since the bay contains bottom water of high salinity, this
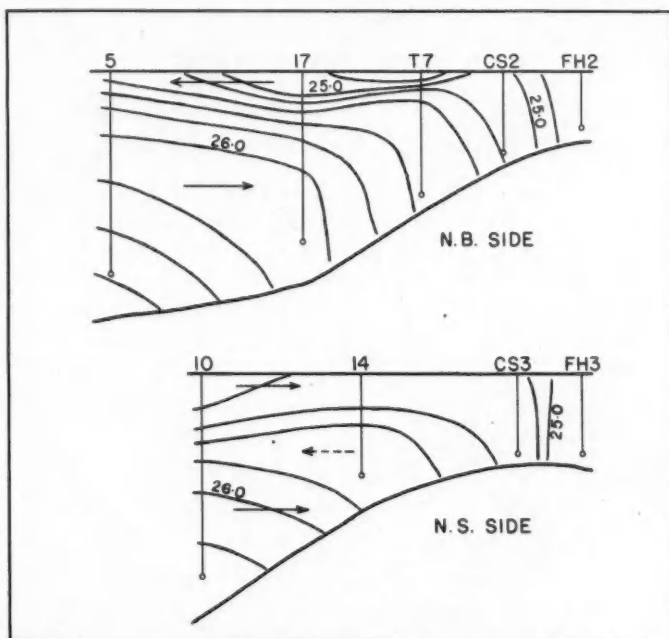
FIGURE 16.   Longitudinal σ_t (density) sections, bay of Fundy, June 15-18, 1932.

must necessarily come from the gulf of Maine. During the winter months there is a minimum amount of fresh water flowing into the bay and owing to the low stability and strong winds there is free interchange at all depths between the bay and the neighbouring gulf. This winter water might remain at the bottom of the bay during the spring and summer, gradually getting warmer and fresher by dilution from above. From the observations, however, it can be seen that the deep water, for example at 100 metres at stations S3 or 17, gets progressively salter from $32.5^0/_{00}$ at the end of April to $33.2^0/_{00}$ early in September. This shows that there is a steady inflow of salt deep water from the gulf of Maine which more than compensates for the dilution from vertical mixing. Reference

6

to figure 16 along with the following explanation should make the mechanism of interchange at different levels clear.

There are two systems of movements which may occur in a mixing zone such as the bay of Fundy. If normally stratified waters are mixed by tidal stirring, as on the Nova Scotian side of the bay, there will be an inflow of light surface water, an outflow of intermediate mixed water and an inflow of bottom water. If, however, there is a considerable addition of fresh water at the mixing zone, as on the New Brunswick side of the bay, there will be only two movements, a surface outflow and a bottom inflow. Both these systems of movements resulting from the mixing of stratified waters have been produced experimentally and described by Hachey (1934B). In figure 16 the directions of flow in each

FIGURE 17. Temperature and density at 0 and 75 metres, bay of Fundy, June 15-18, 1932.

section are indicated by the arrows. In the bay of Fundy the bottom water right across the deep channel moves inward, but the surface water runs outward near Grand Manan and inward near Nova Scotia. The existence of the inward current along the Nova Scotian side of the bay has been proved by many drift bottle returns as well as by Mavor's analysis of Dawson's current measurements, and its explanation lies in the different mixing conditions on either side of the bay. The mixed water produced on the Nova Scotian side must flow either outward to the gulf of Maine as a sub-surface current or across to the New Brunswick side to augment the supply of bottom water which is steadily being consumed by the Saint John mixing mechanism. The former does not seem likely, as there has never been any evidence for it, and presumably its effect would have been noticed in Dawson's current measurements. Between Grand Manan

and Saint John the bottom water is gradually lightened by vertical mixing, so that off Tiner point the upper boundary of the relatively homogeneous bottom water is the $\sigma_t = 25.4$ surface, which occurs at a depth of 20 metres about 10 miles (18 km.) off shore. It seems highly probable that the mixed water of density $\sigma_t = 25.3 - 25.5$ which is found from surface to bottom off Digby (sta. 12, fig. 15) and as far north as Port Lorne (sta. CS3, figs. 15, 16) moves across the bay
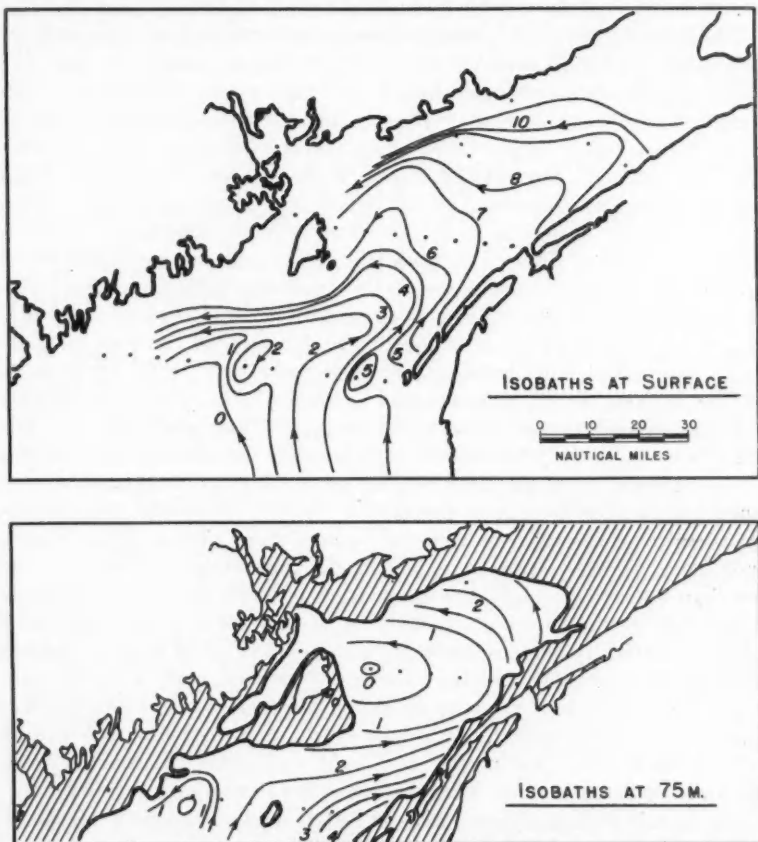
FIGURE 18. Current fields in June as shown by dynamic isobaths. Figures show dynamic centimetres above the lowest point in each isobaric surface. Current velocity in knots is approximately equal to the traverse gradient in dyn. cm./mile.

towards Saint John, merging with the deep water which has come in more directly on the New Brunswick side. Thus in figure 16 the juxtaposition of the two systems of mixing modifies the one in the Nova Scotian section and the flow of the intermediate mixed water is not outward as indicated by the broken arrow but at right angles to the section and across to the New Brunswick side. It is easily seen that this combination of the two mixing systems offers much less

resistance to flow, since there is no longer a layer moving in the opposite direction to the water above and below it. Nevertheless there will still be an outward pressure at the intermediate depths on the Scotian side, so that the inflow will still be greatest at the surface and bottom but negligible at intermediate depths. Since the heavier bottom water moves inward on both sides the density isolines near the bottom will slope downward from the Maine or New Brunswick side towards the Scotian side, as for example the $\sigma_t = 26.4$ line in figure 15.

Further evidence of the residual movements in the bay of Fundy is given by the dynamic topographic charts in figure 18. These charts are based on the same data as the sections in figure 15, but they must not be considered as accurate representations of the currents, since the method of calculating the dynamic heights of the stations is inherently inapplicable to shallow waters with strong bottom currents. Corrections have been made throughout for unequal depths of adjacent stations, but often the correction was as great as the difference in dynamic height to which it was applied. Furthermore, the distance between the sections allows great freedom in sketching in the isobaths and using the same calculated heights at the stations one may draw very different sets of isobaths. Nevertheless the salient features of the current system are indicated by the isobaths. The velocity in knots is approximately equal to the reciprocal of the distance in nautical miles between successive isobaths. As the stations in the two lower sections are six miles (11 km.) apart it is easy to estimate the current velocity in any region as indicated by the isobaths. The most prominent surface currents are the Saint John current, the westerly outflow towards the Maine coast, and the inflow on the Nova Scotian side. The two closed isobaths in the southernmost section are due to the effect of the bottom configuration of Grand Manan bank and a submarine ridge off Brier island. As has already been explained (sect. 6) they represent failure of the calculations for dynamic height rather than the actual lines of flow of the water. At 75 metres, the water seems to set easterly in the lower portion of the bay and westerly in the upper portion. The lack of continuity of the isobaths at 75 metres in figure 18 is easily understood by reference to figures 15 and 16. The rather rapid easterly flow towards the Scotian coast consists of water which is heavier than $\sigma_t = 25.8$ between Grand Manan bank and Brier island. It is drawn towards the coast because it is being consumed there by vertical mixing, and as it approaches the coast it becomes lighter because of more rapid dilution with water from above. Further up the bay (see fig. 15, stations 13 and 14) the water at the 75 metre level has been diluted to a density of about 25.6, so that here it forms the lower boundary of the layer of mixed water of density $25.3-25.7$ which moves across to the New Brunswick side. At stations 12, 13, and 14 this layer occupies the whole depth of water down to 75 metres, so that its velocity at any one level is insignificant. On the New Brunswick side the 75 metre isobaths again run into the coast because the bottom water is being drawn upward into the Saint John outflow. Such movements illustrate the importance of vertical transport in coastal waters and the consequent necessity for drawing vertical sections.

The variation in the stability of the surface layer from month to month is particularly interesting and is important for the production of phytoplankton.

According to Braarud an increase in stability in the bay of Fundy has a beneficial effect on the production of phytoplankton. Owing to the frequency of cloudy days and the turbidity of the water the thickness of the layer in which light is sufficient for good growth is only about 20 metres, and the effect of vertical mixing is to deplete the plant stock by removing it from the thin productive layer. Figure 19 shows the areas of greatest stability of the upper 25 metres for the months of May, June, August and September. There appears to be high stability in May as a result of the fresh water from the spring freshets, but it decreases to a minimum in June as the light surface water is dissipated. In August the rising temperature of the surface water again increases the stability, until in September decreasing air temperature and strong winds combine to reduce it
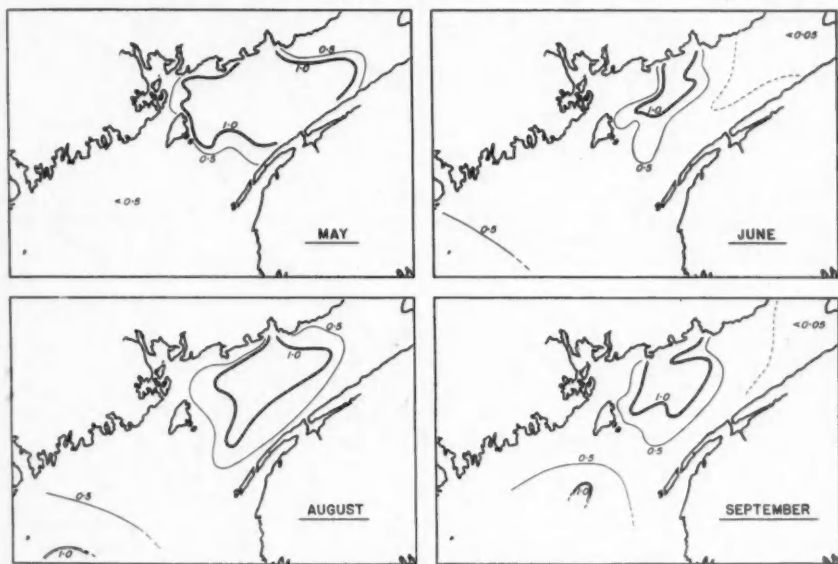
FIGURE 19. Stability of surface layer as measured by the difference in σ_t at 25 metres and 0 metres.

once more. It probably does not increase again until the following spring. As there are no available data on the monthly variation in stability over the bay from year to year an attempt has been made to follow this by using the differences in temperature at 0 and 20 metres at the regular Atlantic Biological Station no. 5, in the Outer Quoddy region. It would seem that the time of occurrence of the stability minimum must depend on the time and volume of the spring freshets and also on the amount of sunshine in the summer months. It may be still further complicated by variations in the rate of horizontal interchange due to wind action. The tendency seems to be for years with maximum freshets in April (1921, 1927) to have a stability minimum in July or early August, while maximum freshets in May (1926, 1928, 1930) are followed by an earlier stability

minimum in June or early July.   Also in 1924 when the Saint John outflow was unusually concentrated in May, there was only a slight decrease in stability in June.   These results are based on data which are too isolated to be conclusive and they are presented only in view of their possible importance.
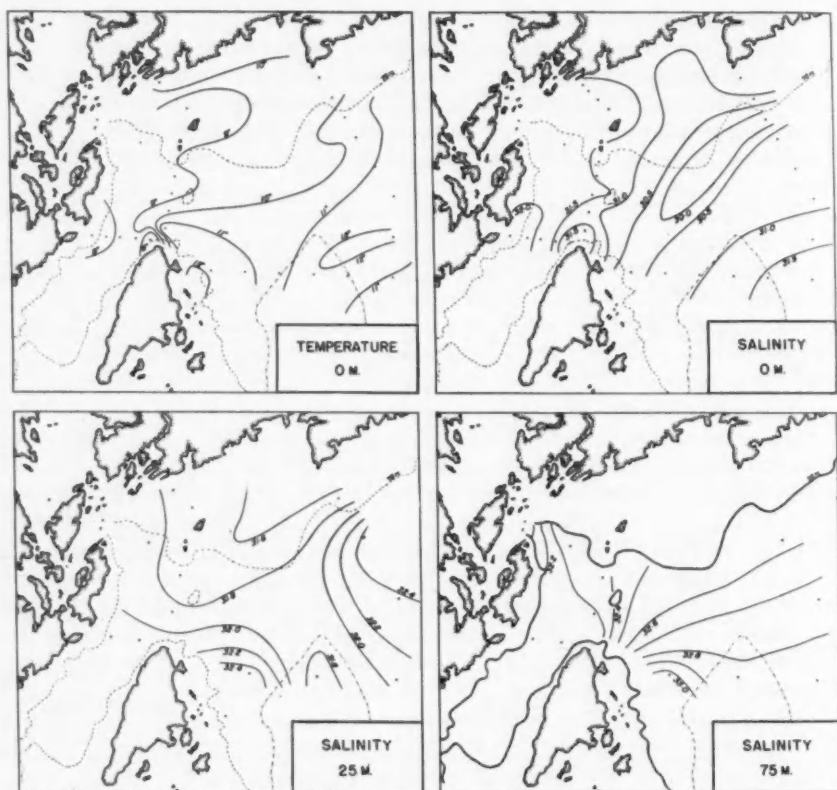
FIGURE 20.   Salinity and temperature, Outer Quoddy region, July 7, 1932.

8. SUMMER CONDITIONS IN THE QUODDY REGION AND THE ADJACENT PART OF THE BAY

The interchange of water between the Quoddy region and the neighbouring parts of the bay is so variable that the observations obtained have not been sufficient to show the movements clearly.   In such a restricted region the supply of fresh water, the tides and the winds, not only at the time but during the previous week, will all modify the resultant water movements.   In particular, owing to the relation of the region to the Saint John current, the effect of the tide is to remove certain waters from the region on the flood while the ebb introduces new waters from outside.   Radical changes in distribution will occur in six hours

and the only way of getting a detailed picture of the movements is to make simultaneous observations from as many boats as possible, and to repeat these observations under various conditions of tide, wind and season. Observations
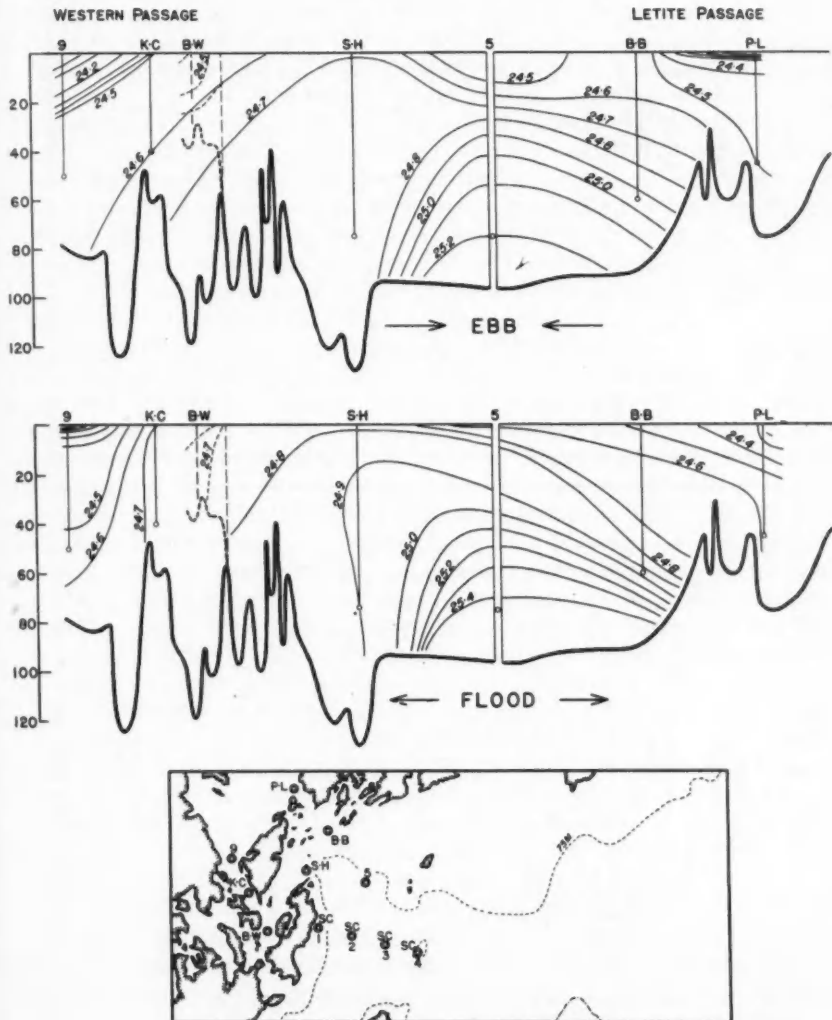
FIGURE 21. σ_t (density) in passages, ebb and flood, July 26, with key to stations.

taken from a single boat, however frequently, can give little information as to movements. On August 5, 1931, a surface temperature survey was carried out by four boats simultaneously, both at high water and at low water (fig. 22). On July 7,

1932, using only two boats, a complete hydrographic series was ru⸱ ⸱⸱ low water. Figure 20 shows the distribution of salinity at 0, 25 and 75 metr⸱s and also the surface temperatures. The remaining data may be found in the tables. The
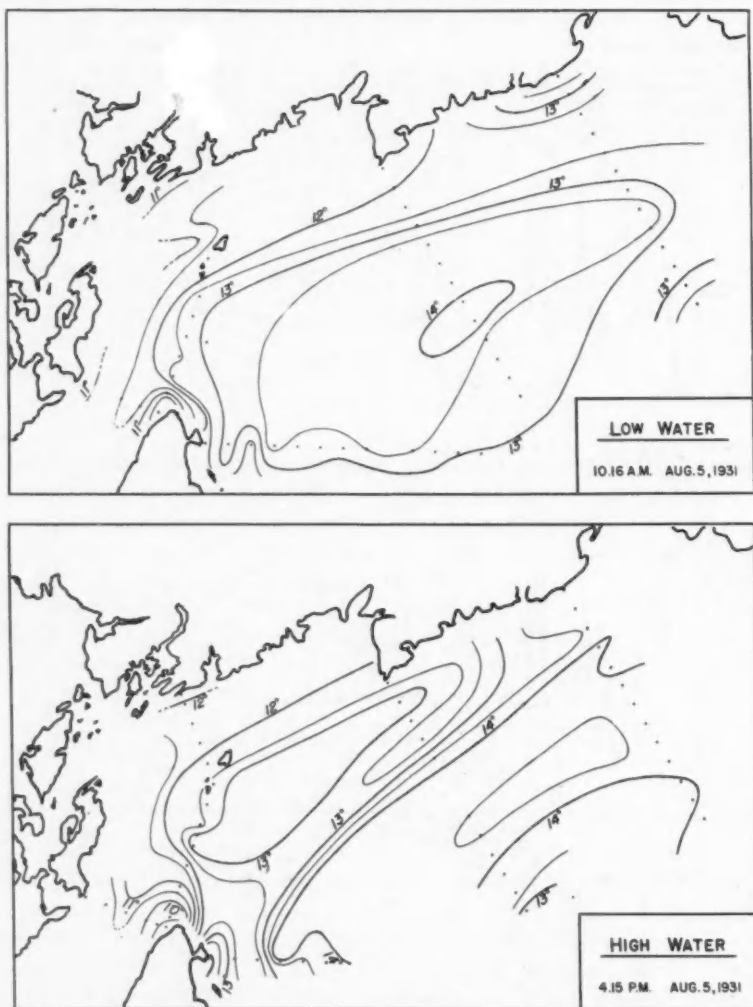
FIGURE 22. Surface temperature off the Quoddy region, at low water and high water, August 5, 1931.

question of greatest interest in this region is the effect of the Quoddy mixing mechanism and the part which it plays in determining the circulation of the Outer Quoddy region. Figure 21 shows the simultaneous values of σ_t in the two passages from Passamaquoddy bay out to station 5, during the last half of each

tidal flow on July 26. These sets of observations present a fairly complete picture of conditions, but it is difficult to deduce from them the details of the water movements. Certainly the mixing mechanism of the passages does not appear to dominate conditions in the Outer Quoddy region. In figure 21 the flood tide water entering the passage between Spruce island and Head harbour (station S-H) is not the stratified water from station 5, only about four miles (7.4 km.) away, but homogeneous water which probably emerged from the passages on the previous ebb tide. It appears that a large fraction of the water which comes out of the passages on the ebb tide returns into them on the succeeding flood and that the residual outflow of mixed water over a complete tidal interval is quite small. Nevertheless since there is a considerable drainage of fresh water into Passamaquoddy bay there will be an outflow of mixed water from the passages in the upper layers and a consumption of heavier water from below. The source of this heavier water and the subsequent path of the outflow are of great interest, but they are both somewhat uncertain owing to the smallness of the quantities involved in comparison with the tidal transport.

The following is the writer's interpretation of the July 7 survey. The most prominent surface water (see fig. 20) consists of a wide band of light fresh water outside the 75 metre contour, sweeping past Lepreau towards Grand Manan. $(S < 31^0/_{00}, \sigma_t < 24.0, t > 10°)$. This band is bordered by the heavier salter water in the middle of the bay and by similar water $(S > 31.5^0/_{00}, \sigma_t > 24.0, t < 9°)$ in the Outer Quoddy region. The latter is very sensitive to wind and tidal conditions and seems to play no definite role in the mixing mechanism, which draws its light water from the inner bays. At a depth of from 20 to 50 metres the mixed product of the mechanism flows first southward and then eastward, the boundaries of its path being indicated by the $31.8^0/_{00}$ and $32.0^0/_{00}$ isohalines at 25 metres (see fig. 20). This deduction is based on the argument that vertical mixing is not very effective at this depth since it is above the region of influence of bottom friction and below the depth of normal wind stirring. The density isolines or the isohalines will therefore run in the direction in which the water moves. Of course the isoline at a certain depth only marks the boundary of the water at that depth and it may flow at right angles to the isoline by rising to a higher level. But in that case the layer becomes thin and soon loses its identity. At or below 75 metres, on the contrary, the water is subject to vertical mixing and will become lighter as it progresses, so that the direction of flow will be at right angles to the isolines, except where the depth is much greater than 75 metres. The 75 metre section in figure 20 shows that the heaviest or most saline water moves from the deepest part of the bay towards the coastal slope, a portion entering the Outer Quoddy region and moving towards the passages. Some of this deep water at the passages may also originate in the bay as water of the same density and salinity, but at smaller depths. The part played by Grand Manan channel remains obscure, but since it is so nearly homogeneous any interchange with the Quoddy region is probably determined by combinations of wind and tide.

The dynamic heights of the water off Lepreau and at sta. 5 were given for May. Dynamic heights obtained later in the summer are: July 7, at L4, 7314.94 cm., and at sta. 5, 7317.02; Sept. 4, at L3, 7316.78 cm., at L4, 7315.93
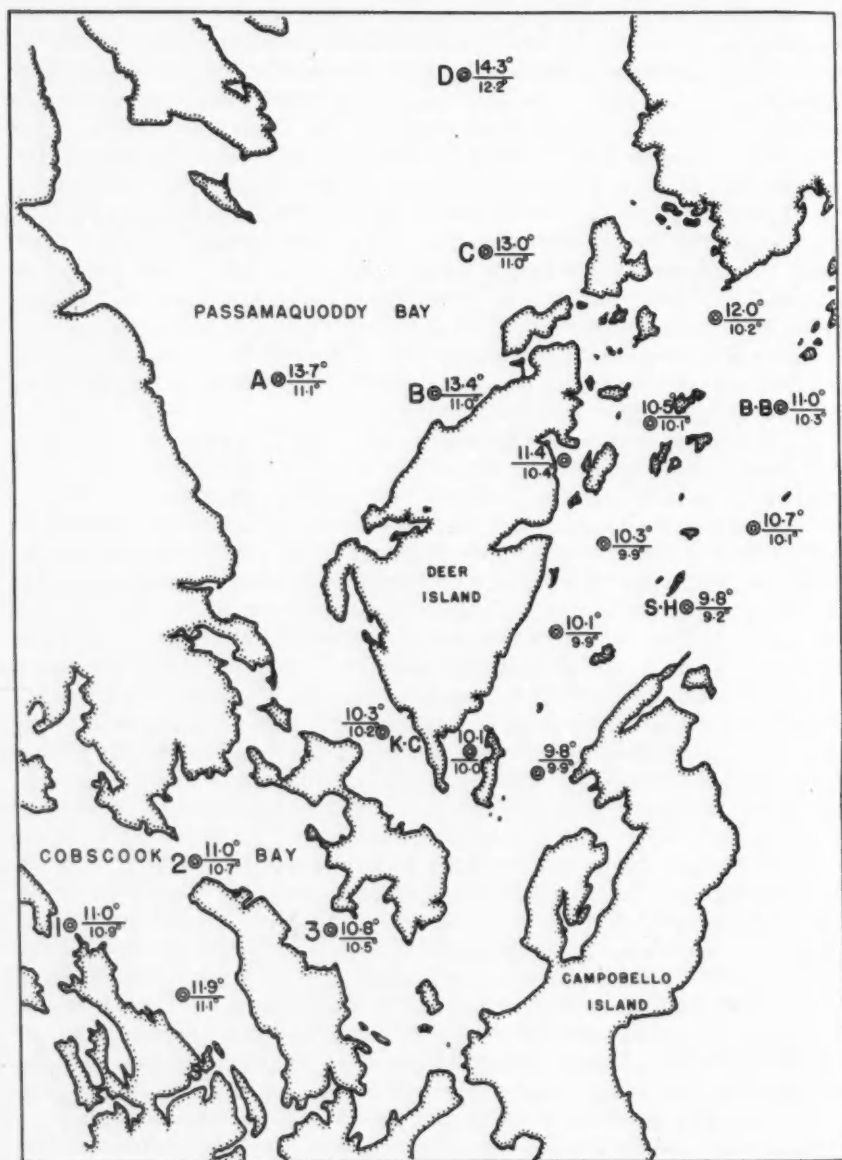
FIGURE 23. Temperature at surface (upper figures) and 5 metres (lower figures), Inner Quoddy region, high water, Aug. 5, 1932.

cm.; and Sept. 12 at sta. 5, 7317.70 cm. Thus in July and September, as well as in May, the water at sta. 5 is dynamically higher than at L4. This means that throughout the summer the average density at sta. 5 is such that gravity forces are called into play which prevent the surface Saint John current from entering the region. An inspection of figure 19 shows that throughout the summer the stable surface layer includes the Saint John current and excludes the Quoddy
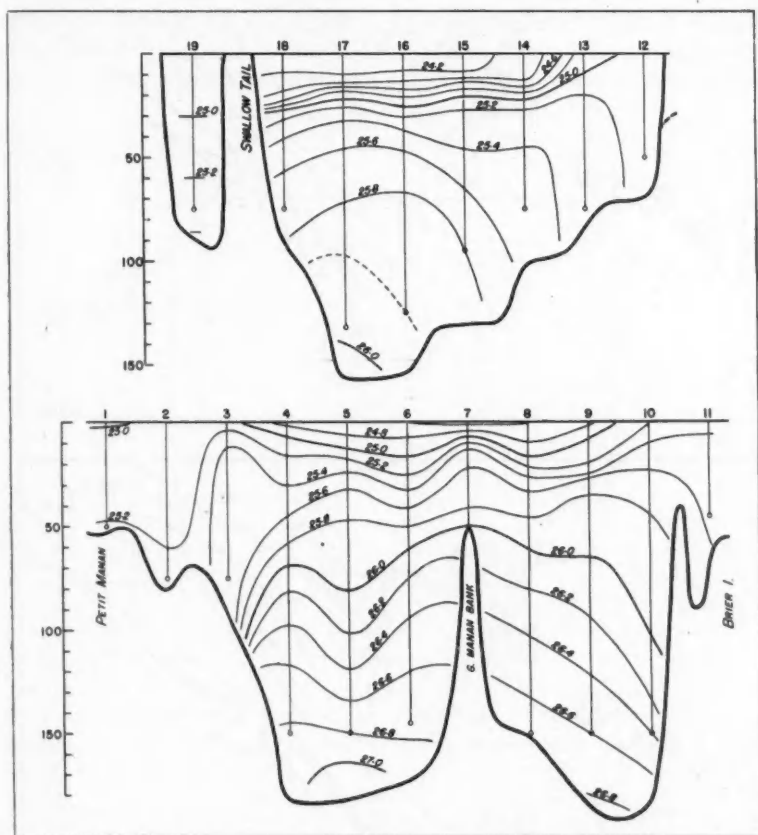
FIGURE 24. σ_t (density) sections, bay of Fundy, September 4-7, 1932.

region. Consequently a greater absorption of heat takes place at sta. 5 than beneath the stable insulating layer, so that on July 7 the average temperature of the water to a depth of 75 metres is 6.9° at L4 and 7.4° at sta. 5, while in September the difference is still greater, 9.7° at L4 and 10.8° at sta. 5. This difference in absorption of heat tends to make the water at sta. 5 lighter. If the mixing in the region were reduced the surface water would become more stable and the average temperature less. This would mean a decrease in the dynamic height

and therefore less resistance to the Saint John current, which might then enter the Quoddy region.

On August 5 at high water a rapid survey was made of the waters in the
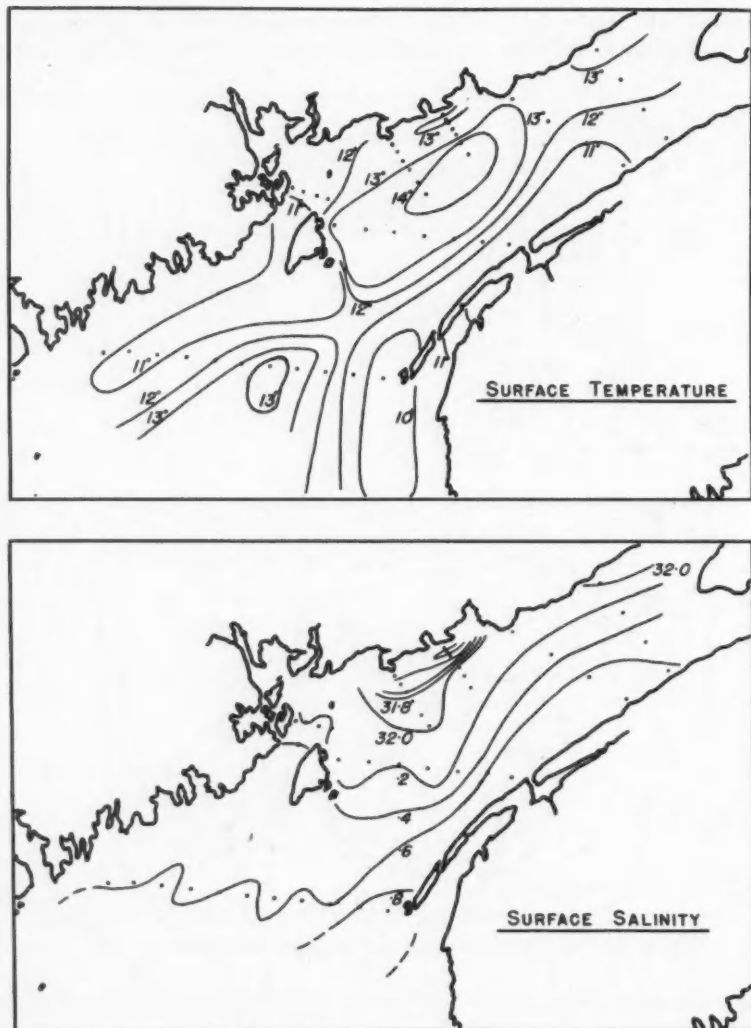
FIGURE 25.   Surface temperature and salinity, September 3-7, 1932.

passages and in Passamaquoddy bay, using two boats.   The temperatures of the surface layer at 0 and 5 metres are shown in figure 23.   The stations in Cobscook bay were taken at the same stage of tide on the following day, so that

the whole set of observations may be regarded as simultaneous. The low surface temperature of 9.8° in the passages is indicative of the unusual conditions which exist in this region.

9. September Hydrographic Survey of Bay of Fundy

Between September 3 and 8 the June survey was repeated in order to observe the seasonal progress. On the whole there was remarkably little change in the distribution and only a slight decrease in the actual values of the densities, since the increase in temperature was nearly balanced by the increase in salinity. Figure 24 shows the density distribution for the two main sections across the
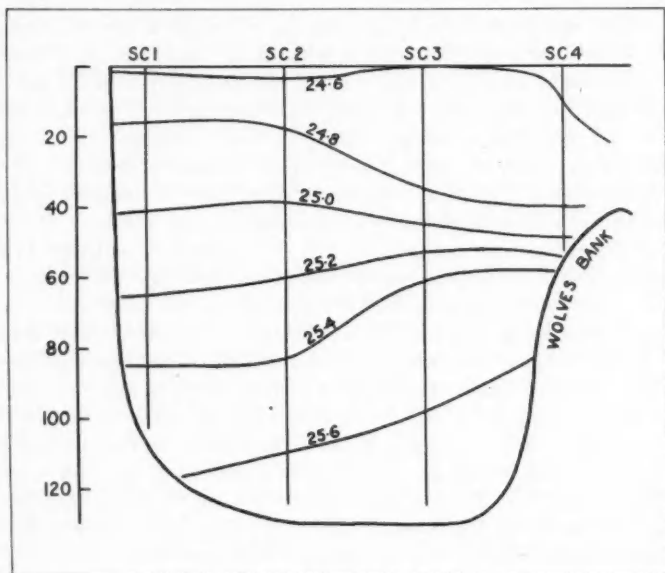
FIGURE 26. σ_t (density) section, Campobello island to Wolves bank, September 7, 1932. For key to stations, see figure 21.

bay and these should be compared with the same sections taken in June (fig. 15). Figure 25 shows the surface distribution of salinity and temperature. As before the warmest water occupies a pool in the middle of the bay while the warm gulf of Maine water is found as far north as Grand Manan bank. The maximum temperature is nearly 15° as compared with 10° in June. The light surface water is more widespread than in June, since it is due to high temperature rather than to the low salinity of the Saint John outflow. A section taken from Schooner cove on Campobello island across the Outer Quoddy region to the Wolves bank at low water is shown in figure 26. The distribution of the isolines suggests an outflow from the passages moving south at an average depth of 50 metres. Sim-

ultaneous sections were taken across the south end of Grand Manan channel and
from Machias bay to Seal island, in the region to the south of the channel, on
September 29 after a few days of strong winds. Both sections seemed to indicate
a surface current moving southward from the channel.

The observations given in this paper should be supplemented by those of
Mavor, whose work was carried out in the latter part of the summer. Owing to
lack of space it is impossible to give any further discussion of the results obtained
from the September survey.

10. SUMMARY

Winter temperatures in Passamaquoddy bay are lower than in the bay of
Fundy but not as low as in bays further south, such as Cape Cod bay. In the
Outer Quoddy region the vertical distribution of temperature is determined by
the fresh water discharge into the neighbouring bays. From November to
February the coldest water is at the surface, but around March 1 it is found as a
sub-surface layer at 25 metres. In 1932 this distribution was maintained until
late April. During March and early April a rise in temperature in the Fundy
deep indicates an inflow of warmer water from the gulf of Maine.

On the arrival of the spring freshets at Saint John a stratified surface layer
flows over the homogeneous Fundy water towards Grand Manan. In early May
water with a temperature between 1° and 2° is found beneath this insulating
layer, and this water is then the coldest throughout the bay of Fundy or the gulf
of Maine. The decreased absorption of heat beneath this layer sets up a density
distribution which keeps the Saint John current out of the Quoddy region. In
the Outer Quoddy region maximum spring tides at this season increase the salinity
at all depths and decrease stratification. The drift through Grand Manan
channel is into the region, but small. The outflow from the Quoddy region as a
whole is also small. Further observations in May show the existence of a central
eddy off Swallow Tail where the Saint John current runs out over water of in-
creasing depth (see Part I, sect. 5). Mixing by the Manan shoals is of local
importance, but as in the case of most banks and shoals the mixed water remains
in the mixing region.

A general June survey of the bay of Fundy shows that the most prominent
surface movements are the Saint John current, the westerly Fundy outflow and
an inflow on the Scotian side. The Fundy outflow originates to the east of Grand
Manan, and flows westerly in a thick surface layer towards the Maine coast,
along the border of a body of homogeneous coastal water which extends from
Grand Manan channel to Petit Manan. The very slow northeasterly drift in
this homogeneous water may be due to the prevailing SW winds. On both sides
of the bay of Fundy below 100 metres there is an inflow of bottom water from
the gulf of Maine which more than compensates for dilution from vertical mixing.
Except for modifications by the Saint John current and the central eddy, the
water at any level gets progressively lighter as the head of the bay is approached.
The dominant feature of the bay is the turbulence within the layer of frictional
influence of the bottom, which is from 20 to 50 metres high. The stability of the
upper 25 metre layer has a June minimum with maxima in May and August,

decreasing again in September and remaining very low until the following spring. The circulation in the Outer Quoddy region is rather indeterminate and the outflow from the Quoddy passages does not appear to produce any dominant effect. Indications are that it travels first southward and then eastward at a depth of from 20 to 50 metres, passing between the Wolves bank and Grand Manan. Below this outflow there is a slow inflow of heavy water which is gradually diluted by turbulence as it moves from the Fundy deep into the Quoddy region.

In September the density distribution and the water movements in the bay are practically the same as in June, though the temperatures are of course much higher.

Hachey (1934, A) has attempted to use vertical temperature gradients as an indicator of the replacement of bay of Fundy waters, using the differences beween the annual ranges of temperature at surface and 20 metres, and at 20 and 90 metres. Observations were made once each month at a single station in the Outer Quoddy region (sta. 5). However, the annual temperature range as determined from such occasional observations may easily have an error of plus or minus one degree, and, as the difference of the ranges at two levels is on the average only about one degree, it is clear that they cannot be calculated from such inadequate data. In addition the station chosen is certainly not representative of the bay of Fundy.

In a subsequent paper, Hachey (1935) states that the extent of the renewal of the bay of Fundy water "will depend upon the amount of the salter bay of Fundy water that the reversing falls consumes". It will be shown (Part III, sect. 6) that, while the rate of inflow of the bottom water does depend largely on the discharge of the Saint John river, the mixing in the reversing falls is quite unimportant compared with the subsequent mixing outside the river estuary. Hachey's conclusion that the inflow "can be represented by a stream 20 miles in width, 20 fathoms in depth and with a velocity of 5 miles per day", a rate which "corresponds with the known circulation from drift bottle investigations", is very misleading since it infers that the inflow is on the surface. His calculation is based exclusively on surface salinities, but no such calculation can be applicable to the bay of Fundy where the inflow consists mostly of heavy bottom water.

PART III. GENERAL CONCLUSIONS

A summary of the conditions and movements observed in the bay of Fundy has been given in the final section of Part II. We shall now proceed to discuss certain hydrological phenomena which have been studied in connection with the bay of Fundy, but which are of quite general interest.

1. ESTUARIAL MIXING

In connection with a study of the Saint John river outflow it has been found that the estuarial features at Saint John are somewhat different from usual and lead to unusual hydrographic conditions in the neighbouring region. In such estuaries as Penobscot bay, Maine, or the Severn estuary in England, vertical

mixing is effective and though there is little difference in density from top to bottom at any one station, the density increases as we approach the open sea. The change from the estuary to the sea is a gradual one, both with regard to depth and to the physical properties of the water. At Saint John, however, the estuary is short, consisting only of the harbour which is very shallow except for a dredged channel. The bottom of the open bay of Fundy then drops away with a gradient of about 10 metres per mile (1.8 km.) down to 75 metres. Thus the river water, instead of gradually losing its identity as it travels down a long estuary, flows directly out to sea as a strongly stratified layer, about 10 metres thick. It retains its lower boundary as far as Grand Manan island, a distance of 40 miles (74 km.). The resistance to vertical mixing is remarkably great and the explanation seems to be as follows. Vertical mixing is effected by the transport of water particles from one layer into another. This is accomplished by the eddies produced at the interface between two layers moving at different velocities. Quantitatively the energy available to effect vertical mixing is proportional to the square of the vertical velocity gradient. The resistive force which prevents mixing is a gravity force, and the work done against it is proportional to the density gradient. Hence the continued existence of a strongly stratified surface layer above homogeneous water is dependent on the relative values of the density gradient and the velocity gradient. Now in an estuary or a shallow bay bottom friction produces a strong vertical velocity gradient and a considerable fraction of the kinetic energy of the water goes into eddy motion. The energy in these eddies is then used up by destroying the vertical density gradient. But the conditions at Saint John are such that a strongly stratified surface layer, practically filling the shallow harbour, flows out over deep homogeneous water. With the increase of depth the gradient of velocity becomes small, although the actual tidal velocities are high. So the stratified surface layer is not destroyed in spite of the rapid movements of the tidal streams. Of course the volume of the river outflow is also important for the maintenance of the density gradient in the surface layers as they spread over the Fundy water. The addition of salter water in the mixing mechanism increases the total outflow, though it decreases the density gradient, and it is questionable whether the reversing falls increase or decrease the extent to which the Saint John waters are noticeable in the surface layers. Another consequence of the balance between the production of eddy energy and the work done in layer destruction is that the stratified surface layer will rapidly disappear as such if it runs over a region of shallow water where the gradient of velocity is increased. It should therefore be borne in mind that the continuation of a surface layer over deep water and its disappearance over shallow water does not exclude the possibility that a considerable amount of the surface water may have flowed over the shallow region.

2. The Formation and Maintenance of Homogeneous Water

It is a matter of common observation that currents flow clockwise around a bank, and that the water above the bank is almost homogeneous, as for example in the case of Georges bank (see Bigelow, figs 186 and 203). We shall establish the general principle that any area which contains homogeneous water, however

this may be formed, will be conspicuously lacking in permanent residual currents. The only internal force which can maintain a current is a gravity force due to density distribution, measured quantitatively by the number of solenoids. Since the retarding force of friction exists everywhere, a current can only continue where there are solenoids to propel it and overcome friction. While there are few, if any, solenoids in homogeneous water there will be a great number around its periphery where the isosteric surfaces must slope if there is a transition from homogeneous to stratified water. Consequently we will find a gravity propelled current only at the periphery. On the other hand variable wind currents will occur in the homogeneous water much more easily than elsewhere since there are no gravity forces to oppose such currents. Bodies of water such as we have been discussing are found close to a coast line which is on the right of a current flowing parallel to the coast. The homogeneity is produced by continual turbulence in the tidal streams in shoal water, either close to shore or over a large bank. Examples are Georges bank, the head of the bay of Fundy, and Grand Manan channel with the shoal region to the south and southeast of it.

If a homogeneous region is to be permanent it must continually receive or produce sufficient light water to keep its density lower than the mean density of an equal depth of water just beyond it. This is simply the condition that there shall be an outward gravity force on the surface water to balance the inward dynamic force of the peripheral current. For otherwise the current and the peripheral stratified water would move in, and homogeneity would be destroyed. Georges bank at once furnishes examples of both these cases. At the north-western edge of the bank, near cape Cod, the hydrostatic forces drive light surface water onto the bank too rapidly for homogeneous water to be formed and we find stratified water over the bank. At the eastern edge the water above the bank is homogeneous and lighter than an equal depth of the water just off the bank, so that there is an outward hydrostatic force to keep the periphereal current away from the bank. Furthermore this condition is maintained because there is a supply of light water available to the mixing region from the east and north. On the other hand a bank which has no local supply of light water will be covered by water which is heavier than the surrounding water, since the isosteric surfaces are rasied by the momentum of the water which is forced up the slopes of the bank. There will be no peripheral current to retain the water above the bank, and so it will not remain long enough to become homogeneous. Such a case is illustrated by Grand Manan bank (see Density sect., fig. 15), where the isosteric layers are raised above the bank, but not destroyed. The stability of the water above the bank may even be increased, as it was on September 4. The dynamic isobaths at the surface for such a region will, of course, show a depression above the bank, and this is not to be interpreted as due to a cirulatory surface current, but to the upwelling on the slopes of the bank.

Another important factor which helps to lighten the homogeneous water is the greater absorption of heat. In the summer stratified layers at the surface prevent transfer of heat downwards, but the free vertical motion in homogeneous water facilitates it. The average temperature of a vertical column above the bank is considerably higher than that of an equal column off the bank. For

7

example, a station on Georges bank in June varies from 10° at the surface to 9.7° at 60 metres while a station in the channel to the northeast of the bank averages just over 6° for the same depth ("Atlantis" stations 1673 and 1658). Furthermore, the average salinity at the bank station is higher than at the channel station, but its higher temperature is sufficient to keep it lighter. This differential absorption of heat is important, but it is essentially a secondary factor since it only comes into action when the water has been maintained in a homogeneous state for some time. However, it may be that the selective freshening of the mixed water in the spring lightens it sufficiently to prevent the inroads of the periphereal currents only just long enough for the selective heating to take the major role in lightening the mixed water.

3. The Effect of a Shoaling Bottom on Tidal Waters

The effects of bottom friction on coastal waters are most easily understood by resolving the complex motion of the water into its two major components, the oscillatory tidal motion and the residual current or drift. In a purely oscillatory tidal motion, turbulence spreads upward through the water, breaking down stratification, until finally the whole vertical column is rendered homogeneous. Since on the whole the water does not move away from the source of turbulence the effect must be cumulative. At each station in the region considered the water will finally be homogeneous from surface to bottom. However, the rates of interchange vertically and horizontally are of the same order while the vertical depth is only a very small fraction of the horizontal, so that mixing may be complete vertically while the density changes considerably from station to station. Now consider the effect of a residual current which we may assume to be on the surface, since the horizontal distribution of fresh water takes place on the surface. As soon as horizontal motion occurs the effects of mixing at one particular place are no longer cumulative and will only extend to a height above bottom determined by the degree of turbulence and by the rate of removal of the mixed water. The water will then become stratified in the upper layers, and will tend to become homogeneous only within a certain distance from the bottom. This distance depends both on the degree of turbulence, and on the rate of removal of the products of mixing. Where we have a shoaling bottom the height of influence will reach into higher and lighter layers as the depth becomes less, so that in succession the isolines will turn downward, and while the water for some distance above bottom will be homogeneous at each station it will become lighter as we move to a shallower station. If we refer to figures 15 and 16 and examine the behaviour of the density isolines in relation to the bottom we see that the lines turn downward as they come within 20 to 50 metres of a gradually shoaling bottom, but are unaffected when they meet a steep bottom slope. When the bottom rises steeply the volume of water within which turbulence occurs is small and probably no individual portion of water remains in this region for more than a fraction of its tidal path. The distribution of the density isolines in figures 15 and 16 has been discussed in more detail in Part II, section 7.

4. CURRENT SYSTEMS PRODUCED BY TIDAL MIXING

If stratified waters are mixed by tidal stirring the mixed water moves away from the region at an intermediate depth while surface and bottom waters flow in towards the region. When fresh water is supplied directly to the mixing region the current system is reduced to a surface outflow and a bottom inflow. In the case of the bay of Fundy both cases occur in adjacent regions and the resulting system is still further modified. The reader is referred to Part II, sect. 7, for a complete discussion of the resulting current system. In particular it is to be noted that the juxtaposition of the two systems is not peculiar to the bay of Fundy but may occur wherever the fresh water inflow to a bay or gulf is concentrated along one side.

5. QUANTITATIVE DETERMINATION OF THE EFFECT OF MIXING, WITH EXAMPLES FROM THE BAY OF FUNDY

Since the term mixing is used for various effects associated with turbulent motion it is necessary to state clearly which effect we wish to measure quantitatively. For certain purposes the amount of motion is of interest, for it will determine the destructive forces which are brought to bear on any organism or material moving or suspended in the water, or it may determine the availability of certain foods and chemical substances necessary to life. Such effects are largely biological, but they are often included in forming a mental picture of the effects of mixing. In this determination we are concerned exclusively with the physical effect of turbulent motion in changing the mass distribution of the water so as to maintain residual currents to or from the mixing region. We shall attempt to measure not the energy of turbulent motion but the work done against gravity when mixing causes the density of the upper layers to be increased at the expense of the lower. Neither the mixing produced by convection currents, as in the winter overturn, nor the mixing from the external force of the wind, need concern us when comparing regions where the climatic conditions are appreciably the same.

Consider a mixing region in which fresh water is added locally so that there is a resultant inflow of heavy bottom water and an outflow of mixed water in the upper layers. It is assumed that the rate of addition of fresh water is known as well as the distribution of density throughout the mixing region. The following symbols will be used:

V_0=cu. m./sec. of fresh water added at the surface within the region

V_b=cu. m./sec. of bottom water, density ρ_b or σ_b, drawn in from a depth z_b metres

z_m=depth in metres of outflow of mixed water of density ρ_m or σ_m at boundary of region

σ_1 or ρ_1=mean density, surface to z_m

σ_2 or ρ_2=mean density, z_m to z_b

Since the water moves horizontally as well as vertically during the mixing, σ_1 and σ_2 are not the mean densities at any one station but must be derived by studying the density distribution along the path of the currents. The funda-

mental expression for the work done in raising V cu. m. of water of density σ through h metres of mean density σ' is

$$\text{Work} = Vg(\sigma-\sigma')h \times 10^8 \text{ ergs} \dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

In the case of continuous mixing, the conservation of mass leads to

$$V_b = \frac{\sigma_m}{\sigma_b - \sigma_m} \times V_0 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

and the power, or rate of work, necessary to maintain the new density distribution is

$$\text{Power} = V_0 \left\{ \sigma_1 z_m + \frac{\sigma_m(\sigma_b - \sigma_2)}{(\sigma_b - \sigma_m)}(z_b - z_m) \right\} g \times 10^{-5} \text{ kilowatts} \dots\dots (3)$$

In the particular case of complete mixing from surface to depth z, where z is also the depth of inflow of heavy bottom water from outside the region

$$\text{Power} = V_0 \sigma_m z g \times 10^{-5} \text{ kilowatts} \dots\dots\dots\dots\dots\dots\dots\dots (4)$$

In the last two equations the result may be converted to horsepower by multiplying the number of kilowatts by 1.34.

We shall now apply these results to the bay of Fundy and to some of the individual mixing mechanisms which it contains. The results should be instructive as to the relative importance of such mechanisms.

BAY OF FUNDY, JUNE

Consider the mixing within the section from Petit Manan to Brier island, shown in figure 15. We shall choose such values for the various quantities in equation (3) as shall lead to a conservative estimate of the mixing in the bay.

$$V_0 = 1,500 \quad \sigma_b = 26.5 \text{ at } z_b = 140$$
$$\sigma_m = 25.3 \text{ at } z_m = 10$$
$$\sigma_1 = 25.0, \quad \sigma_2 = 25.99$$

V_0 is obtained from the mean discharge into the bay of Fundy for June given in figure 3. All the other quantities except σ_1 are obtained by inspection of the density section in figure 15. For σ_1 the surface density at the points of fresh water inflow must be considered as well as σ_m. Fortunately, errors in σ_1 do not affect the final result greatly. σ_2 may be taken as the arithmetic mean between σ_m and σ_b, or the characteristic distribution of density between σ_m at z_m and σ_b at z_b may be plotted and the mean obtained graphically. This gives a value somewhat higher than the arithmetic mean because the density in the lower levels does not change as rapidly with depth as in the upper levels. Substituting the values given in equation (3) we get

Mixing Power, bay of Fundy, $= 24,200$ kilowatts $= 32,450$ H.P.

HEAD OF THE BAY, JUNE

Consider the region above the cape Spencer section (see figs. 1, 15, and 16). Here the water is all within the frictional influence of the bottom and stirring is so active that at every station the water is almost homogeneous from surface to

bottom. Hence we can use equation (4) to calculate the mixing power. Figure 16 shows that the outflow of mixed water, which takes place on the New Brunswick side, lies between $\sigma_t = 25.0$ and 25.2. We shall take

$V_0 = 230$ (see fig. 3, regions 5, 6, 7), $\sigma_m = 25.1$, $z = 60$

and substituting in equation (4) we get

Mixing Power, head of bay $= 3,400$ kilowatts $= 4,550$ H.P.

QUODDY PASSAGES, JULY

Most of the fresh water discharged into the bays enters the Western passage, and the mixing in this passage finally achieves a homogeneous column, between $\sigma_t = 24.7$ and 24.8, which oscillates between stations K-C and S-H (see fig. 21). Some of this water is probably further mixed in Letite passage to about 24.5, so that if we take the mean density of the mixed water from the passages as $\sigma_m = 24.7$ we shall be close to the true value. For July, 1932, the mean fresh water discharge into Passamaquoddy bay was 2530 cu. ft./sec. or 71.6 cu. m./sec. To allow for the small discharge into Cobscook bay we shall take $V_0 = 80$ cu. m./sec. The average depth of complete mixing and the depth from which bottom water is drawn may be taken as 80 metres. Substituting in equation (4) the values

$V_0 = 80$, $\sigma_m = 24.7$ and $z = 80$, we get
Mixing Power, Quoddy passages $= 1,550$ kilowatts $= 2,080$ H.P.

SAINT JOHN RIVER ESTUARY, JUNE

Data given by Hachey (1935) may be used to calculate the density of the mixed water in Saint John harbour in June, 1930. Mean densities for the strongly stratified mixed water are 7.62 at the surface and 24.43 at 5 metres. From 5 metres the density increases very slowly to 24.57 at 15 metres. For June, 1930, the mean fresh water discharge at Saint John was 44,800 cu. ft./sec., or 1,270 cu. m./sec. Hence

$V_0 = 1270$ $\sigma_b = 24.57$ at $z_b = 15$
$\sigma_m = 16.03$ at $z_m = 2.5$
$\sigma_1 = 11.82$; $\sigma_2 = 23.64$

and substituting in equation (3) we get

Mixing Power, Saint John estuary $= 640$ kilowatts $= 858$ H.P.

6. CONCLUSIONS

The foregoing calculations show that of the total mixing in the bay of Fundy which is effective in producing a circulation, 14% takes place at the head of the bay, 6% in the Quoddy passages, and 3% in the estuary of the Saint John river. These figures will vary with the season but they give a good quantitative basis for comparison of the various regions and lead to the following conclusions. The most important cause of the residual currents is the combination of the turbulent mixing *throughout the bay* with the large inflow of fresh water at Saint John. At the head of the bay, where the height of frictional influence of the bottom reaches

the surface over a large area, we might expect the mixing to be large. On the contrary, the effective mixing is only 14% of that throughout the bay, because very little of the energy of turbulent motion is required to maintain the mixed condition by doing work against gravity. The effective mixing in the short and shallow Saint John estuary is very small, and the direct effect of the reversing falls on the currents of the bay is negligible. By this we mean that most of the work done in mixing the Saint John fresh water is supplied outside of Saint John harbour. The mixing produced by the Quoddy passages is important locally, but only amounts to about 6% of the total mixing in the bay of Fundy. It seems very unlikely that this amount of effective mixing, or any variation therein, can seriously affect the general circulation of the bay or of the neighbouring part of the gulf of Maine.

WINTER TEMPERATURES, 1931-32

In Passamaquoddy bay, midway between Navy island and Lewis cove, temperatures at 0, 10, and 25 metres:

Oct. 15, ——— , 10.55, 10.39; Oct. 20, 11.0, 10.32, ———; Nov. 10, 9.6, 9.08, 9.12; Nov. 16, 8.17, 8.45, 8.88; Nov. 23, 8.8, 8.72, 8.81; Nov. 30, 7.8, 8.02, 8.38; Dec. 7, 6.4, 6.72, 7.22; Dec. 17, 4.7, 5.90, 6.13; Dec. 21, 4.7, 5.09, 5.38; Jan. 5, 3.2, 3.47, 3.53; Jan. 11, 3.0, 3.55, 4.00; Jan. 12, 3.3, 3.46, 3.90; Jan. 25, 2.7, 3.42, 3.84; Mar. 1*, 0.9, 0.81, 0.88.

In Outer Quoddy region, at station 5, temperatures at 0, 10, 25, 40, 75, metres:

Oct. 9, 11.1, 10.99, 10.93, 10.50, 9.47; Oct. 21, 10.21, 10.10, 10.07, 10.02, 9.78; Nov. 11, 9.5, 9.37, 9.36, 9.43, 9.51; Nov. 17, 9.06, 9.01, 9.09, 9.09, 9.09; Nov. 23, 9.5, 9.02, 9.17, 9.23, 9.29; Dec. 2, 8.2, 8.36, 8.49, 8.71, 9.19; Dec. 9, 7.6, 7.80, 7.56, 7.89, 8.40; Dec. 21, 6.4, 6.65, 6.70, 6.70, 6.65; Jan. 5, 5.3, 5.40, 5.49, 5.56, 5.52; Jan. 26, 4.1, 4.38, 4.52, 4.60, 4.74; Feb. 2, 3.2, 3.84, 4.18, 4.27, 4.39; Mar. 5*, 1.5, 1.40, 0.90, 1.62, 1.92.

North of Grand Manan island, lat. 44° 49.5′ N, long. 66° 42.5′ W, temperatures at 0, 10, 25, 40, 75 metres:

Nov. 12, 9.5, 9.48, 9.47, 9.46, 9.47; Dec. 11, 8.1, 8.05, 8.06, 8.09, 8.09; Jan. 29, 4.5, 4.59, 4.62, 4.64, 4.94; Mar. 5*, 2.3, 2.20, 2.50, 2.20, 2 23.

Bay of Fundy, east of Grand Manan, lat. 44° 37.5′ N, long. 66° 23′ W, temperatures at 0, 10, 25, 40, 75 metres:

Nov. 12, 9.3, 9.24, 9.50, 9.54, 9.07; Dec. 11, 7.3, 7.23, 7.31, 7.99, 8.38; Jan. 29, 4.7, 4.82, 4.86, 5.04, 5.45; Mar. 5*, 2.0, 2.82, ———, 2.96, 2.70.

*Temperatures given for March are uncorrected readings.

TABLES OF TEMPERATURES, SALINITIES AND DENSITIES
SPRING AND SUMMER, 1932

In the following tables the station data are given in the first column in this order: station number or name, date, time of first and last observations, wind and tide. The other four columns contain the depth in metres and the corresponding values of temperature, salinity and σ_t.

INDEX TO STATIONS

Regular stations are shown on maps in the following figures:

Other stations in the Quoddy region used occasionally are located as follows:

SW stations lie between South Wolf and Bishop rock, Grand Manan, at the following distances from South Wolf: SW1, $2\frac{1}{4}$ miles (4.2 km.); SW2, $4\frac{1}{4}$ miles (7.9 km.); SW3, $5\frac{1}{2}$ miles (10.2. km.)

EW stations lie between East Wolf and Deadman head, at the following distances from East Wolf: EW1, $1\frac{1}{2}$ miles (2.4 km.); EW2, $2\frac{1}{2}$ miles (4 km.); EW3, $3\frac{3}{4}$ miles (7 km.);

C stations, used on July 7 only, are on a line crossing Grand Manan channel from West Quoddy head, their positions being marked on figure 20.

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STATION	M	TEMP	SAL	σ_t
5, Apr 19	0	2.5	30.17	24.10
	10	2.59	30.72	24.53
16.19-50	25	2.36	31.20	24.93
strong S	40	2.38	30.55	24.41
L.W.16.25	75	2.36	30.97	24.74
5, Apr 19	0	2.64	30.55	24.40
	10	2.71	30.72	24.52
22.27-23.06	25	2.69	31.08	24.80
Light NW	40	2.57	31.24	24.95
H.W.22.40	75	2.54	31.91	25.48
5, Apr 20	0	3.0	-----	-----
	10	2.76	31.13	24.84
11.04-50	25	2.59	31.22	24.92
Light NW	40	2.58	31.27	24.97
H.W.11.05	75	2.51	31.85	25.44
5, Apr 20	0	2.81	31.31	24.99
	10	2.95	31.31	24.98
17.07-41	25	2.62	31.40	25.07
Light NW	40	2.56	31.51	25.16
L.W.17.15	75	2.51	31.35	25.03
19, Apr 22	0	2.5	31.65	25.28
	10	2.49	31.71	25.32
23.55-0.27	25	2.46	31.71	25.32
Calm	40	2.48	31.71	25.32
H.W.0.11	60	2.49	31.71	25.32
	100	2.51	31.71	25.32
19, Apr 22	0	2.48	31.18	24.90
	10	2.46	31.67	25.30
6.16-54	25	2.45	31.87	25.46
Light NW	40	2.39	31.92	25.51
L.W.6.34	60	2.36	32.00	25.57
	100	2.44	32.09	25.63
9, Apr 22	0	4.13	29.07	23.10
	10	3.59	29.58	23.54
12.31-13.21	25	3.25	30.37	24.20
Fresh NW	40	3.11	30.62	24.41
H.W.12.39	75	2.99	31.09	24.79
9, Apr 22	0	4.20	28.42	22.57
	10	3.98	29.31	23.29
18.44-19.19	25	3.05	30.35	24.21
Fresh NW	40	2.95	30.53	24.35
L.W.18.56	75	2.90	30.70	24.49
5, Apr 25	0	2.96	31.47	25.10
	10	2.79	31.51	25.15
9.27-10.07	25	2.69	31.60	25.22
Light NW	40	2.68	31.62	25.23
L.W.9.13	75	2.48	31.83	25.43
5, Apr 25	0	3.4	31.13	24.79
	10	2.80	31.49	25.13
14.54-15.17	25	2.79	31.51	25.15
Strong S	40	2.73	31.62	25.23
H.W.15.14	75	2.47	31.62	25.25
Centre Pass.	0	3.7	30.23	24.04
Bay, Apr 25	10	3.29	30.41	24.23
17.10-17.21	25	3.02	30.79	24.55
5, Apr 26	0	3.0	31.24	24.91
	10	2.93	31.36	25.02
10.17-39	25	2.96	31.40	25.05
Fog	40	2.71	31.62	25.23
L.W.10.10	75	2.76	31.49	25.13

STATION	M	TEMP	SAL	σ_t
5, Apr 26	0	2.9	31.53	25.15
	10	2.90	31.56	25.18
15.50-16.11	25	2.79	31.64	25.25
E, fog	40	2.69	31.64	25.25
H.W.16.15	75	2.79	31.64	25.25
T1, Apr 30	0	4.9	16.91	13.43
	5	2.78	23.44	18.73
11.42-54	10	1.51	31.00	24.83
Light E	25	1.36	31.15	24.95
L.W.14.15	35	1.35	31.80	25.48
T2, Apr 30	0	4.5	17.97	14.29
	5	2.83	25.12	20.06
12.17-46	10	1.86	30.12	24.11
Light E	25	1.43	31.80	25.47
	35	1.42	31.80	25.47
T3, Apr 30	0	4.7	17.79	14.14
	5	2.14	28.84	23.06
13.24-36	10	1.45	31.42	25.16
Light E	25	1.36	31.76	25.45
	40	1.44	31.85	25.51
T4, Apr 30	0	4.3	18.51	14.73
	5	1.64	31.06	24.86
14.12-50	10	1.50	31.27	25.05
Light E	35	1.48	31.83	25.50
	60	1.48	31.89	25.54
T5, Apr 30	0	5.2	17.34	13.75
	5	2.62	24.94	19.92
15.19-49	10	1.63	29.61	23.71
Light SxE	35	1.56	31.26	25.03
	60	1.56	31.94	25.57
T6, Apr 30	0	4.6	18.96	15.07
	5	2.11	28.77	23.00
16.19-36	10	1.45	29.99	24.03
Light SxE	25	1.47	31.87	25.53
	40	1.45	31.96	25.60
	75	1.49	31.96	25.60
T7, Apr 30	0	4.3	21.09	16.77
	5	2.05	28.51	22.82
17.17-37	10	1.49	31.44	25.18
Light S	25	1.34	31.80	25.48
	40	1.38	31.87	25.54
	75	1.89	32.07	25.66
L1, May 3	0	3.5	28.37	22.59
	5	3.03	28.62	22.83
3.42-55	10	1.89	31.09	24.88
NW cloudy	25	1.48	31.82	25.48
L.W.4.21	35	1.45	31.83	25.50
L2, May 3	0	4.3	26.42	20.97
	5	3.41	27.65	22.03
4.26-42	10	1.71	31.53	25.23
NW cloudy	25	1.48	31.78	25.45
	50	1.50	31.82	25.48
L3, May 3	0	4.7	24.07	19.09
	5	3.15	27.57	21.99
5.19-41	10	1.79	31.55	25.24
Fresh NW	25	1.58	31.94	25.57
	40	1.85	32.07	25.66
	75	1.98	32.14	25.71

STATION	M	TEMP	SAL	σt
L4, May 3	0	5.2	24.34	19.27
	5	2.70	28.75	22.95
6.06-26	10	1.89	31.94	25.55
Fog	25	1.94	32.18	25.74
	40	1.99	32.18	25.74
	75	2.04	32.21	25.76
L5, May 3	0	5.0	26.42	20.92
	5	2.61	31.13	24.85
7.00-30	10	2.35	31.65	25.29
Fog	25	2.05	32.10	25.67
	60	2.07	32.14	25.70
	100	2.07	32.18	25.73
L6, May 3	0	5.1	27.85	22.04
	5	3.48	31.53	25.10
7.58-8.19	10	3.52	31.64	25.18
Fresh NW	25	2.16	32.20	25.74
	60	2.08	32.20	25.75
	100	2.09	32.23	25.78
S1, May 4	0	3.2	29.43	23.46
	5	2.95	29.97	23.90
4.24-52	10	2.21	31.36	25.07
Light NW	25	1.64	31.82	25.47
L.W.5.03	40	1.78	31.98	25.59
	75	2.79	32.34	25.80
S2, May 4	0	3.5	28.82	22.95
	5	3.44	29.29	23.32
5.47-6.01	10	1.94	32.00	25.60
Light NW	25	2.64	32.29	25.77
	60	2.73	32.30	25.78
	100	2.99	32.36	25.80
S3, May 4	0	4.1	29.70	23.59
	5	3.86	30.64	24.36
6.39-7.07	10	3.50	31.62	25.16
Light NW	25	3.60	32.09	25.53
	40	3.79	32.34	25.71
	60	3.63	32.52	25.87
	100	3.24	32.59	25.97
S4, May 4	0	4.1	31.64	25.13
	5	3.95	31.64	25.14
7.55-8.16	10	3.81	31.67	25.19
Light NW	25	3.70	32.34	25.72
	60	3.62	32.52	25.88
	100	3.61	32.59	25.94
SW2, May 4	0	3.13	31.53	25.13
	5	2.97	31.53	25.14
16.15-53	10	2.89	31.58	25.19
Strong S	25	2.79	31.67	25.28
L.W.17.16	40	2.42	31.85	25.44
	60	2.48	31.85	25.44
	100	1.88	31.94	25.55
P1, May 18	0	4.0	31.69	25.18
	7½	4.10	31.71	25.18
16.42-55	20	4.12	31.74	25.21
S, hazy	35	3.69	31.74	25.25
P2, May 18	0	4.0	31.87	25.33
	7½	3.86	31.91	25.37
17.28-41	20	3.87	31.91	25.37
L.W.15.56	35	3.80	31.91	25.38

STATION	M	TEMP	SAL	σt
P3, May 18	0	3.9	31.94	25.39
	7½	3.77	31.94	25.40
18.14-49	20	3.79	32.01	25.45
	35	3.89	32.14	25.54
	60	4.07	32.29	25.64
WH3, May 18	0	6.7	30.66	24.06
	10	6.70	30.91	24.27
19.53-20.15	25	4.79	31.85	25.23
Light W	50	4.37	32.52	25.80
	100	4.37	32.74	25.97
WH2, May 18	0	6.3	30.50	23.99
	10	4.64	31.09	24.64
21.08-35	25	4.71	32.01	25.36
H.W.22.15	50	4.50	32.39	25.69
	100	4.16	32.66	25.93
WH1, May 18	0	5.8	30.26	23.86
	10	4.61	30.91	24.40
22.56-23.07	25	2.95	31.82	25.37
Light W	50	3.03	32.21	25.68
S1, May 19	0	5.9	30.34	23.91
	7½	3.62	31.33	24.92
8.25-50	20	3.64	31.51	25.07
Light N	40	3.47	31.67	25.22
L.W.4.28	75	3.43	32.36	25.76
S2, May 19	0	6.4	30.26	23.79
	5	5.40	30.59	24.16
9.22-10.05	10	4.31	31.20	24.76
	25	3.06	32.01	25.52
	50	2.96	32.18	25.66
	100	3.90	32.61	25.92
S3, May 19	0	7.1	30.25	23.69
	5	4.10	31.33	24.88
10.34-11.04	10	4.10	31.83	25.29
H.W.10.45	25	4.69	32.30	25.59
	50	4.32	32.48	25.78
	100	4.30	32.63	25.90
S4, May 19	0	8.5	29.92	23.25
	5	6.07	30.35	23.91
11.30-12.04	10	5.38	31.58	24.95
Calm	25	4.45	32.09	25.45
	50	4.32	32.39	25.71
	100	4.16	32.68	25.95
S1, May 19	0	7.2	30.05	23.52
	7½	4.48	30.88	24.49
13.15-29	20	3.61	31.40	24.99
	40	3.14	31.85	25.38
	75	3.30	32.14	25.60
19, May 19	0	4.6	31.53	24.99
	7½	4.26	31.53	25.02
14.44-58	20	3.71	31.82	25.30
L.W.16.50	40	3.69	31.85	25.34
	75	3.50	31.76	25.28
9, May 19	0	7.3	29.65	23.20
	5	7.08	29.72	23.29
17.48-18.00	10	6.81	29.90	23.45
Strong SW	25	5.06	31.00	24.53
	50	4.92	31.08	24.60

STATION	M	TEMP	SAL	σt
Letite Pass.	0	4.5	31.51	24.99
May 20	5	4.28	31.51	25.01
	10	4.32	31.53	25.02
12.06-18	25	4.61	31.67	25.11
H.W.11.34	35	4.03	31.67	25.17
Letite Pass.	0	5.9	30.82	24.29
May 30	5	5.38	30.82	24.35
	10	5.29	30.91	24.44
9.29-9.50	25	4.77	31.33	24.81
H.W.8.32	35	4.49	31.51	24.99
EW2, May 30	0	7.6	28.98	22.63
	5	6.38	30.14	23.69
11.03-15	10	5.93	30.55	24.08
	25	4.33	31.71	25.16
	40	3.65	31.80	25.30
5, May 30	0	6.8	30.44	23.88
	10	5.76	30.66	24.18
11.51-12.04	25	5.03	31.24	24.72
SE, clear	40	4.26	31.69	25.15
½ebb	75	3.65	32.14	25.57
SW2, May 30	0	7.6	28.98	22.63
	5	6.18	29.51	23.22
13.00-21	10	4.82	31.20	24.71
SE clear	25	4.54	31.35	24.85
	60	4.00	32.01	25.44
	100	4.03	32.39	25.74
19, May 30	0	7.2	30.03	23.50
	5	5.39	30.82	24.35
14.10-30	10	5.26	31.24	24.69
SW clear	25	4.64	31.53	24.99
L.W.14.25	50	4.08	31.85	25.30
	90	3.83	32.32	25.90
5, May 31	0	5.7	30.95	24.42
At H.W.	5	5.53	30.97	24.45
9.43-10.07	10	5.40	30.97	24.46
Strong SW	25	4.93	31.46	24.90
H.W.9.19	40	4.55	31.56	25.02
	75	3.85	32.18	25.77
5, May 31	0	5.7	31.15	24.57
At ½ebb	5	5.50	31.15	24.59
	10	5.47	31.15	24.59
12.27-51	25	4.58	31.51	24.98
Light SW	40	4.39	31.62	25.08
½ebb at 12.17	75	3.88	32.00	25.63
5, June 2	0	6.0	31.08	24.48
At ½flood	5	5.17	31.31	24.76
7.40-8.05	10	5.16	31.35	24.79
Light NW	25	4.68	31.65	25.08
H.W.10.40	40	4.46	31.76	25.19
	75	4.79	32.05	25.38
SW2, June 2	0	6.1	31.08	24.47
	5	5.67	31.09	24.53
9.09-59	10	5.57	31.13	24.57
Light NW	25	5.11	31.44	24.87
Clear,calm	40	4.85	31.64	25.05
	60	4.30	32.07	25.45
	100	4.34	32.21	25.56

STATION	M	TEMP	SAL	σt
5, June 2	0	7.0	31.08	24.36
At H.W.	5	5.81	31.17	24.56
10.41-11.03	10	5.53	31.24	24.66
Calm	25	5.12	31.35	24.79
H.W.10.40	40	4.73	31.58	25.02
	75	4.20	31.98	25.39
5, June 2	0	5.8	31.29	24.67
At ½ebb	5	5.46	31.33	24.74
13.49-14.07	10	5.39	31.33	24.75
Fresh S	25	4.98	31.49	24.92
½ebb at 13.40	40	4.79	31.60	25.03
	75	4.24	32.16	25.53
Wilson's	0	5.6	31.31	24.71
Beach,June 2	5	5.68	31.31	24.70
15.10-25	10	5.65	31.31	24.71
Moderate S	25	5.61	31.33	24.72
	35	5.59	31.33	24.72
5, June 2	0	6.6	30.90	24.26
At L.W.	5	6.19	31.31	24.65
16.43-17.02	10	5.52	31.36	24.76
S, clear	25	5.17	31.55	24.92
L.W.16.40	40	5.14	31.58	24.97
	75	4.45	31.89	25.29
9, June 9	0	7.4	30.62	23.95
	5	7.10	30.82	24.14
9.35-10.00	15	6.48	31.09	24.43
After strong	30	6.46	31.13	24.47
S, L.W.9.13	50	6.34	31.20	24.54
Q1, June 13	0	6.5	31.82	25.00
	5	5.99	31.85	25.09
11.43-54	10	5.79	31.92	25.17
Cloudy	25	5.73	31.92	25.18
L.W.12.43	35	5.59	31.92	25.20
Q2, June 13	0	6.6	31.58	24.80
	5	6.21	31.62	24.88
12.16-38	10	6.03	31.65	24.93
SW,cloudy	25	5.47	31.83	25.14
	40	5.47	31.92	25.21
	75	4.77	32.29	25.57
Q3, June 13	0	6.3	31.80	25.01
	5	6.03	31.80	25.05
13.03-21	10	5.97	31.80	25.06
	25	5.47	31.80	25.11
	40	5.36	31.96	25.25
	75	4.93	32.16	25.46
Q4, June 13	0	6.0	31.87	25.11
	5	5.84	31.87	25.13
13.43-14.05	10	5.83	31.87	25.13
SW,cloudy	25	5.38	31.94	25.23
	40	5.43	31.98	25.25
	75	5.12	32.09	25.38
MC1, June 13	0	5.5	32.00	25.27
	5	5.39	32.00	25.28
11.44-58	10	5.38	32.00	25.28
SW, clear	25	5.37	32.05	25.32
L.W.12.43	50	5.34	32.05	25.32

STATION	M	TEMP	SAL	σt
MC2, June 13	0	5.7	32.00	25.24
	5	5.46	32.00	25.27
12.25-39	10	5.36	32.00	25.28
L.W.12.43	20	5.31	32.01	25.30
	40	5.31	32.01	25.30
	75	5.29	32.01	25.30
MC3, June 13	0	5.8	31.94	25.18
	5	5.45	31.94	25.22
13.08-24	10	5.37	31.98	25.26
	20	5.32	31.98	25.27
	40	5.31	31.98	25.27
	75	5.30	31.98	25.27
MC4, June 13	0	5.9	31.96	25.19
	5	5.43	31.96	25.25
13.57-14.11	10	5.33	31.96	25.26
	20	5.29	31.96	25.26
	40	5.30	31.96	25.26
	75	5.28	31.96	25.26
MC5, June 13	0	7.1	31.85	24.95
	5	6.02	31.85	25.09
14.39-15.09	10	5.59	31.85	25.14
	25	5.33	31.85	25.17
	50	5.30	31.85	25.17
Q4, June 13	0	6.4	31.87	25.06
	5	5.81	31.87	25.13
17.24-41	10	5.68	31.87	25.15
Light SW	25	5.43	31.87	25.18
Clear	40	5.44	31.89	25.19
	75	5.44	31.96	25.24
Q3, June 13	0	6.5	31.91	25.08
	5	5.59	31.91	25.19
18.03-24	10	5.43	31.91	25.20
	25	5.36	31.91	25.21
	40	5.36	31.91.	25.21
	75	5.35	31.94	25.23
Q2, June 13	0	6.8	31.92	25.05
	5	5.47	31.92	25.21
18.45-19.06	10	5.48	31.92	25.21
Light SW	25	5.37	31.92	25.22
H.W.19.05	40	5.35	31.96	25.25
	75	5.31	31.98	25.27
Q1, June 13	0	5.8	31.94	25.18
	5	5.77	31.94	25.19
19.29-40	10	5.71	31.94	25.19
Hazy	25	5.71	31.94	25.19
	35	5.53	31.94	25.21
MC5, June 13	0	6.5	32.01	25.16
	5	6.30	32.01	25.18
17.23-34	10	6.23	32.01	25.19
Calm, clear	25	5.96	32.01	25.22
	50	5.89	32.01	25.23
MC4, June13	0	7.2	31.96	25.02
	5	5.88	31.98	25.20
18.00-21	10	5.74	31.98	25.22
H.W.19.05	20	5.70	32.00	25.24
	40	5.69	32.00	25.25
	75	5.67	32.03	25.28
MC3, June 13	0	8.2	31.89	24.83
	5	6.98	31.89	25.00
18.49-19.02	10	5.80	31.89	25.14

STATION	M	TEMP	SAL	σt
MC3	20	5.61	31.89	25.17
Calm	40	5.51	31.89	25.18
H.W.19.05	75	5.47	31.89	25.18
MC2, June 13	0	7.2	31.83	24.93
	5	5.65	31.83	25.12
19.30-43	10	5.39	31.83	25.15
	20	5.35	31.83	25.16
	40	5.32	31.83	25.16
	75	5.29	31.89	25.20
MC1, June 13	0	5.6	31.85	25.14
	5	5.45	31.85	25.15
20.06-16	10	5.39	31.85	25.16
Calm	25	5.38	31.85	25.16
	50	5.32	31.87	25.19
5, June 14	0	6.7	31.58	24.79
	10	6.70	31.58	24.79
13.26-39	25	6.24	31.62	24.88
SE, fog	40	6.06	31.71	24.97
L.W.13.40	75	4.93	32.03	25.36
Frenchman's	0	11.1	31.83	24.32
Bay, June 15	5	10.48	31.85	24.44
	15	7.13	31.89	24.98
15.04-15	30	6.40	31.92	25.10
Light W,clear	50	5.73	31.96	25.21
1,June 15	0	7.8	31.91	24.90
Petit Manan	5	7.10	31.91	25.00
	15	6.07	31.91	25.13
17.24-35	30	5.96	31.91	25.14
W, clear	50	5.96	31.92	25.15
2, June 15	0	7.0	32.16	25.21
	5	6.19	32.20	25.34
18.37-48	15	5.83	32.21	25.39
	35	5.77	32.21	25.40
	75	5.62	32.27	25.47
3, June 15	0	7.0	32.25	25.28
	5	6.77	32.27	25.32
20.01-13	15	6.06	32.29	25.42
	35	5.84	32.63	25.73
	75	5.83	32.72	25.79
4, June 15	0	9.0	32.54	25.21
	5	8.99	32.54	25.21
21.10-25	15	8.99	32.63	25.29
	35	7.34	32.66	25.55
	75	5.57	33.04	26.08
	150	6.49	34.09	26.79
5, June 15	0	8.0	32.50	25.33
	5	7.68	32.50	25.38
22.35-51	15	6.85	32.59	25.57
	35	5.51	32.79	25.89
	75	5.65	33.15	26.16
	150	6.09	33.75	26.58
6, June 15-16	0	7.3	32.10	25.12
	5	7.28	32.10	25.12
23.45-0.01	15	7.07	32.21	25.24
	35	6.58	32.47	25.50
	75	5.75	32.90	25.94
	150	6.28	33.87	26.65

STATION	M	TEMP	SAL	σ_t	STATION	M	TEMP	SAL	σ_t
7, June 16	0	8.2	32.45	25.26	CS3, June 17	0	6.9	32.27	25.31
	5	8.14	32.45	25.27		5	6.79	32.27	25.32
2.23-34	10	7.49	32.48	25.39	3.05-20	10	6.81	32.27	25.32
	25	6.91	32.57	25.54	Cloudy	25	6.81	32.29	25.33
	40	5.85	32.79	25.85		60	6.80	32.34	25.37
8, June 16	0	9.5	32.48	25.09	CS4, June 17	0	7.0	32.01	25.09
	5	9.49	32.48	25.09		5	7.09	32.07	25.13
3.28-43	15	8.46	32.48	25.25	1.24-37	10	7.10	32.14	25.18
	35	5.91	32.66	25.74	NE, cloudy	25	7.17	32.16	25.19
	75	5.34	32.95	26.04		50	7.23	32.25	25.24
	150	5.89	33.60	26.49	12, June 17	0	7.0	32.30	25.31
9, June 16	0	7.0	32.29	25.30	(Prim Point)	5	7.18	32.34	25.32
	5	6.85	32.43	25.44	12.58-13.08	15	6.98	32.38	25.38
4.43-58	15	6.91	32.54	25.51	Fresh ENE	30	6.90	32.39	25.40
	35	6.08	32.74	25.78	H.W.10.30	50	6.88	32.39	25.41
	75	5.98	32.79	25.84	13, June 17	0	7.5	32.36	25.29
	150	5.76	33.49	26.41		5	7.50	32.39	25.32
10, June 16	0	7.3	32.01	25.05	13.50-14.01	15	6.66	32.43	25.46
	5	7.22	32.03	25.08	NE, overcast	35	6.46	32.43	25.49
5.51-6.07	15	7.12	32.07	25.12		75	6.29	32.45	25.52
	35	6.37	32.20	25.32	14, June 17	0	7.45	32.41	25.34
	75	5.76	32.84	25.90		5	7.40	32.43	25.37
	150	5.66	33.31	26.29	14.50-15.01	15	7.36	32.43	25.37
11, June 16	0	6.8	32.41	25.41	Very rough	35	6.41	32.52	25.57
Brier I.	5	6.77	32.41	25.43		75	5.93	32.63	25.71
	10	6.68	32.45	25.47	15, June 17	0	8.4	32.12	24.98
8.08-19	25	6.62	32.48	25.51		5	8.30	32.12	25.00
	40	6.59	32.50	25.52	15.47-58	20	7.13	32.18	25.20
FH1, June 16	0	7.9	31.04	24.21	NExN, rough	43	5.52	32.32	25.52
	5	7.78	31.06	24.23		87	5.47	32.83	25.93
20.06-17	10	7.76	31.04	24.23	16, June 17	0	8.7	31.78	24.67
Light NE	25	7.79	31.04	24.22		5	8.46	31.78	24.70
Water muddy	35	7.78	31.04	24.23	16.57-17.18	15	6.56	32.12	25.23
FH2, June 16	0	7.0	31.31	24.55		35	5.81	32.48	25.61
	5	7.02	31.31	24.54		75	5.23	32.79	25.93
21.24-37	10	7.03	31.31	24.54		125	5.29	32.94	26.03
Cloudy	25	7.04	31.31	24.54	17, June 17	0	8.25	31.87	24.81
	40	7.03	31.31	24.54		5	8.24	31.87	24.81
FH3, June 16	0	6.7	31.55	24.76	18.13-36	15	7.62	31.91	24.93
	10	6.60	31.55	24.77		35	5.83	32.39	25.54
22.46-23.01	25	6.59	31.55	24.77		75	5.36	32.92	26.01
	40	6.59	31.55	24.77		125	5.34	32.99	26.07
	60	6.58	31.55	24.77	18, June 17	0	7.9	31.15	24.29
FH4, June 17	0	6.5	31.69	24.90		5	7.82	31.15	24.29
	5	6.47	31.69	24.90	19.32-44	15	5.86	31.83	25.10
0.00-12	10	6.43	31.69	24.91	Light NE	35	5.28	32.12	25.39
	25	6.49	31.73	24.93	Calmer	75	4.81	32.63	25.85
	40	6.55	31.76	24.95	19, June 17	0	5.85	31.92	25.17
CS1, June 17	0	6.8	31.55	24.75		5	5.83	31.92	25.17
	5	6.69	31.55	24.76	21.09-20	15	5.79	31.92	25.17
5.57-6.09	10	6.67	31.58	24.79	Light NW	35	5.75	31.92	25.18
Strong NE	25	6.62	31.62	24.83		75	5.73	31.92	25.18
	40	6.47	31.73	24.93	T1, June 18	0	9.7	27.79	21.42
CS2, June 17	0	6.6	31.85	25.01		5	7.57	29.78	23.26
	5	6.47	31.85	25.03	15.31-43	10	6.73	31.33	24.59
4.36-49	10	6.46	31.85	25.03	Hazy	25	6.57	31.60	24.82
Strong NE	25	6.45	31.87	25.05		35	6.54	31.67	24.89
Cloudy	60	6.33	32.00	25.17					

STATION	M	TEMP	SAL	σt
T2, June 18	0	10.3	27.47	21.06
	5	8.71	28.04	21.75
16.02-14	10	6.69	31.51	24.74
Hazy	25	6.59	31.74	24.93
	35	6.52	31.80	24.99
T3, June 18	0	8.6	30.19	23.45
	5	7.40	30.88	24.15
16.30-41	10	6.77	31.49	24.71
Hazy	25	6.57	31.73	24.92
	50	6.28	32.07	25.23
T4, June 18	0	8.3	30.70	23.88
	5	6.95	31.47	24.68
17.02-14	10	6.59	31.73	24.92
WSW,hazy	25	6.37	31.94	25.11
	60	6.17	32.10	25.27
T5, June 18	0	8.8	31.27	24.26
	5	6.49	31.91	25.08
17.34-53	10	6.42	31.92	25.10
	25	6.32	32.18	25.30
	40	6.09	32.18	25.33
	75	6.07	32.18	25.34
T6, June 18	0	9.6	31.64	24.42
	5	7.46	31.91	24.95
18.16-36	10	6.73	32.07	25.18
WSW,hazy	25	6.16	32.23	25.37
	40	5.84	32.27	25.44
	75	5.79	32.29	25.46
T7, June 18	0	10.3	31.58	24.25
	5	9.76	31.62	24.37
19.00-21	10	7.19	32.07	25.11
Strong S	25	5.96	32.29	25.44
	50	5.76	32.36	25.52
	90	5.75	32.36	25.52
5, June 24	0	7.0	31.85	24.96
	5	7.10	31.76	24.88
11.47-12.28	10	7.01	31.76	24.89
Partly cloudy	25	6.90	31.82	24.95
L.W.10.15	40	6.77	31.85	24.99
	75	5.64	32.27	25.47
Cobscook 1,	0	9.0	31.73	24.58
June 28	5	8.99	31.71	24.56
12.15-17	15	8.99	31.71	24.56
Cobscook 2	0	9.0	31.76	24.61
June 28	5	8.76	31.74	24.63
12.35-37	15	8.57	31.76	24.67
Cobscook 3	0	8.7	31.76	24.64
12.56-59	5	8.66	31.74	24.64
June 28	20	8.58	31.74	24.65
Pass. A	0	10.9	30.01	22.95
July 4	5	9.19	31.09	24.06
W, cloudy	10	8.58	31.44	24.42
12.12-23	20	8.31	31.60	24.59
	30	8.21	31.62	24.61
Pass. B	0	11.0	---	---
July 4	5	10.73	---	---
12.50-13.01	10	9.12	---	---
SW, cloudy	20	8.37	---	---
	30	8.05	31.65	24.66

STATION	M	TEMP	SAL	σt
Pass. C	0	11.0	30.82	23.55
July 4	5	8.89	31.36	24.32
13.30-40	10	8.57	31.49	24.46
Strong SW	25	8.00	31.65	24.67
Pass. D	0	9.9	31.15	23.98
July 4	5	9.44	31.24	24.13
14.08-21	10	8.33	31.53	24.52
Strong SW	25	8.27	31.64	24.62
Rain	40	8.15	31.65	24.65
C1, July 7	0	7.7	32.05	25.02
17.08				
C2, July 7	0	7.7	32.14	25.09
	5	7.55	32.14	25.11
17.23-35	15	7.32	32.14	25.14
Moderate SW	35	6.98	32.14	25.19
H.W.14.05	75	6.80	32.23	25.29
C3, July 7	0	8.2	31.85	24.80
17.52				
C4, July 7	0	9.1	31.49	24.38
	5	8.59	31.62	24.55
18.13-26	20	7.30	32.05	25.08
Light SW,fog	50	6.98	32.18	25.22
	100	6.56	32.38	25.43
C5, July 7	0	7.7	32.03	25.01
Bet. Bishop's				
Rock & SW3	0	11.3	31.65	24.14
July 7,19.00				
SW3, July 7	0	9.7	31.13	24.00
	5	9.31	31.24	24.15
19.27-39	20	7.61	31.80	24.84
Light S	50	6.94	32.07	25.15
	100	6.32	32.43	25.51
Bet. SW3&SW1	0	8.7	31.56	24.50
July 7,19.58				
SW1, July 7	0	8.8	31.49	24.43
	5	8.73	31.49	24.44
20.12-25	15	8.40	31.56	24.54
Light SxE,fog	35	7.66	31.74	24.79
L.W.20.25	85	8.06?	31.49?	24.53?
Bet. SW1 &				
South Wolf	0	9.0	31.44	24.36
July 7,20.40				
5, July 7	0	8.9	31.64	24.53
	5	8.87	31.64	24.53
21.07-21	15	7.69	31.78	24.81
	40	7.29	31.96	25.01
	75	6.21	32.38	25.47
EW1, July 7	0	8.2	31.65	24.64
	5	8.21	31.71	24.68
22.02-15	15	8.10	31.74	24.73
Calm, clear	25	8.06	31.76	24.75
	55	6.71	32.10	25.20
EW2, July 7	0	9.0	31.62	24.49
22.28				

STATION	M	TEMP	SAL	σt
EW3, July 7	0	10.0	31.62	24.33
	5	9.80	31.60	24.36
22.41-54	15	8.45	31.73	24.66
Calm, clear	25	7.73	31.78	24.81
	40	7.25	31.94	25.00
Bet. EW3 & Deadman Hd. July 7,23.08	0	10.0	31.53	24.27
S1, July 7 16.41	0	11.8	30.30	23.01
S2, July 7	0	11.1	30.70	23.43
	5	10.83	30.66	23.45
17.10-26	20	7.44	32.29	25.24
Fresh SSW	50	6.34	32.81	25.80
Hazy	90	5.96	33.12	26.10
S3, July 7 17.50	0	10.8	30.99	23.71
S4, July 7	0	11.9	31.33	23.78
	5	11.83	31.31	23.78
18.21-37	15	11.73	31.40	23.87
Moderate SW	35	8.59	32.05	24.89
	75	6.61	32.83	25.79
	125	6.15	33.13	26.08
S5, July 7 19.02	0	11.5	31.56	24.04
S6, July 7	0	10.9	31.89	24.40
	5	11.18	31.87	24.34
19.32-44	20	10.03	31.96	24.60
Moderate SW	50	6.67	32.63	25.62
L.W.20.25	100	5.92	32.97	25.98
Midway S6 to L6,July 7 20.12	0	12.0	31.35	23.77
L6, July 7	0	11.5	30.77	23.42
	5	11.41	30.77	23.44
20.43-56	20	7.54	32.29	25.23
	50	6.37	32.65	25.67
	100	5.95	32.79	25.84
L5, July 7 21.22	0	11.0	30.84	23.57
L4, July 7	0	10.2	30.77	23.65
	5	9.54	31.35	24.19
21.44-56	15	7.51	32.29	25.23
Light WSW	35	6.27	32.45	25.53
	75	6.13	32.56	25.63
L3, July 7 22.10	0	10.8	29.58	22.62
L2, July 7	0	9.3	30.99	23.95
	5	8.57	31.35	24.34
22.27-38	15	8.34	31.56	24.55
	30	8.19	31.67	24.66
	50	7.82	31.82	24.82
L1, July 7 22.50	0	9.1	31.17	24.13

STATION	M	TEMP	SAL	σt
P·L, July 25 At L.W.	0	13.6	30.39	22.74
	5	10.27	31.38	24.10
	10	10.07	31.64	24.34
11.16-29	25	9.71	31.73	24.47
Calm, clear	45	9.64	31.74	24.49
P·L. July 25 At ½Flood	0	9.9	31.76	24.47
	5	9.80	31.74	24.46
	10	9.82	31.74	24.46
14.19-28	25	9.67	31.80	24.53
H.W.17.21	45	9.66	31.80	24.53
P·L, July 25 At H.W.	0	11.5	31.55	24.02
	5	9.92	31.73	24.43
	10	9.73	31.78	24.50
17.18-28	25	9.72	31.80	24.52
Light NW	45	9.70	31.80	24.53
9, July 25 At L.W.	0	13.1	31.08	23.36
	5	10.11	31.67	24.36
	15	9.80	31.82	24.52
11.30-44	30	9.65	31.99	24.62
L.W.11.11	50	9.56	31.99	24.64
9, July 25 At ½Flood	0	11.6	31.51	24.08
	0	12.7	30.88	23.29
	5	10.85	31.51	24.11
14.06-23	15	10.53	31.55	24.19
Light N	30	10.14	31.71	24.38
Clear, hot	50	9.53	31.85	24.59
9, July 25 At H.W.	0	11.4	31.42	23.94
	0	12.6	31.06	23.44
	5	10.82	31.58	24.17
17.16-34	15	10.43	31.60	24.25
	30	9.84	31.89	24.57
	50	9.56	31.92	24.65
P·L, July 26 At ½Ebb	0	12.2	31.35	23.73
	5	10.07	31.65	24.35
	10	9.91	31.69	24.41
9.20-29	25	9.73	31.76	24.49
Clear	45	9.69	31.76	24.50
B·B, July 26 Ebb	0	9.8	31.89	24.58
	5	9.67	---	---
10.15-28	10	9.57	31.83	24.58
SW, clear	30	9.34	31.91	24.67
	60	8.67	32.12	24.94
5, July 26 Near L.W.	0	10.0	31.74	24.43
	5	10.10	31.74	24.41
	10	9.78	31.74	24.47
11.15-35	25	8.87	31.94	24.76
SW, clear	40	8.24	32.09	24.98
L.W.12.00	75	7.79	32.29	25.20
5, July 26 At ½Flood	0	9.7	31.89	24.59
	5	9.35	31.92	24.68
	10	8.98	32.03	24.83
15.15-35	25	8.80	32.09	24.89
Strong S	40	8.08	32.18	25.07
	75	7.45	32.52	25.43
B·B, July 26 Flood	0	10.2	31.80	24.45
	5	9.82	31.85	24.55
	10	9.58	31.85	24.59
16.10-23	30	9.31	31.89	24.66
Strong S	60	8.64	32.14	24.95

STATION	M	TEMP	SAL	σ_t	STATION	M	TEMP	SAL	σ_t
P.L, July 26	0	11.1	31.82	24.30	Indian River	0	10.1	32.05	24.65
Flood	5	10.60	31.71	24.30	Aug 5	5	10.00	32.05	24.67
	10	10.23	31.71	24.36	14.36-38	20	9.95	32.05	24.68
16.58-17.09	25	9.70	31.83	24.56					
Cloudy	45	9.69	31.89	24.59	K·C, Aug 5	0	10.3	31.98	24.56
						5	10.17	31.98	24.59
9, July 26	0	13.7	30.48	22.79	15.16-27	20	10.13	31.98	24.59
At ½Ebb	5	11.01	31.44	24.03	Calm. clear	40	10.01	31.98	24.61
	15	10.03	31.44	24.19					
9.10-21	30	9.76	31.85	24.56	Pass. A	0	13.7	31.17	23.31
Light S	50	9.73	31.85	24.56	Aug 5,16.13-16	5	11.08	31.53	24.08
					Light S,clear	20	10.35	31.91	24.51
K·C, July 26	0	10.5	31.73	24.34					
At Ebb	5	9.79	31.85	24.55	Pass. B,Aug 5	0	13.4	31.46	23.59
	20	9.72	31.85	24.56	16.42-45	5	11.03	31.51	24.08
9.48-51	40	9.65	31.89	24.60	Moderate S	20	10.64	31.76	24.34
B·W, July 26	0	10.55	31.85	24.42	Pass. C,Aug 5	0	13.0	31.53	23.73
At Ebb	5	10.30	31.85	24.47	17.10-12	5	11.04	31.65	24.19
10.22-25	10	10.26	31.85	24.47	S, clear	20	10.48	31.80	24.40
SSW, hazy	20	9.96	31.89	24.55					
					Pass. D,Aug 5	0	14.3	31.06	23.10
S·H, July 26	0	9.6	31.96	24.67	17.43-45	5	12.20	31.33	23.72
At Ebb	5	9.33	31.98	24.72	S, clear	20	10.55	31.83	24.41
	15	9.31	32.00	24.74					
11.05-15	35	9.32	32.03	24.77	B·B, Aug 5	0	11.0	31.76	24.28
L.W.12.00	75	9.27	32.05	24.79	12.57-59	5	10.34	31.87	24.48
					Light SSW	20	9.71	32.01	24.69
S·H, July 26	0	9.4	32.07	24.79	H.W.13.42	50	9.05	32.25	24.98
At Flood	5	9.23	32.07	24.82					
15.33-46	15	9.02	32.12	24.89	White Horse	0	10.75	31.94	24.46
Strong SSW	30	8.87	32.14	24.92	Aug 5	5	10.13	31.94	24.56
H.W.18.20	74	8.91	32.12	24.90	13.23-25	20	9.55	32.10	24.78
						50	8.66	32.36	25.12
B·W, July 26	0	10.0	31.89	24.55					
At Flood	5	9.77	31.91	24.60	S·H, Aug 5	0	9.8	32.07	24.72
16.27-30	10	9.63	31.91	24.62		5	9.20	32.21	24.93
Strong SSW	20	9.55	31.91	24.64	13.49-14.00	15	9.17	32.23	24.95
					Light SW	35?	9.83	32.10	24.74
K·C, July 26	0	9.7	32.00	·24.68	Clear	75?	9.13	32.23	24.96
At Flood	5	9.42	32.00	24.73					
16.59-17.01	20	9.42	32.00	24.73	Windmill Pt.	0	9.75	32.10	24.75
SSW,overcast	40	9.39	32.00	24.73	Aug 5	5	9.87	32.10	24.73
					14.26-29	20	9.88	32.14	24.76
9, July 26	0	11.8	31.47	23.92	Clear	50	9.44	32.14	24.83
At Flood	5	10.38	31.67	24.32					
	15	9.95	31.78	24.47	Cobscook,	0	11.9	31.85	24.19
17.26-37	30	10.00	31.80	24.48	South Bay	5	11.12	31.89	24.36
Strong SW	50	9.86	31.85	24.54	Aug 6, 14.04	10	10.99	31.92	24.41
					H.W.14.25				
Black Ledges	0	12.0	31.65	24.01					
Aug 5	5	10.21	31.89	24.51	Cobscook 1	0	11.0	31.94	24.42
12.36-38	20	9.94	32.01	24.65	Aug 6, 14.34	5	10.86	31.94	24.44
					S, clear	15	10.70	31.94	24.47
Fish I.	0	10.5	31.91	24.48					
Aug 5, 13.01	5	10.10	31.94	24.57	Cobscook 2	0	11.0	31.96	24.44
Light S,clear	20	10.06	31.94	24.58	Aug 6,15.00	5	10.66	31.96	24.49
					S, clear	15	10.04	32.07	24.68
Lords Cove	0	11.4	31.83	24.27					
Aug 5	5	10.38	31.89	24.48	Cobscook 3	0	10.8	32.03	24.53
13.23-25	15	10.22	31.91	24.53	Aug 6,15.26	5	10.54	32.03	24.57
					H.W.14.25	15	10.45	32.03	24.59
Hospital-Bar	0	10.3	32.00	24.58					
Aug 5	5	9.92	32.00	24.65	T1, Sept 3	0	12.9	30.88	23.25
13.50-53	20	9.74	32.09	24.74		5	11.41	31.78	24.22
					17.04-15	15	11.03	32.23	24.64
Casco-Deer	0	10.1	32.10	24.69	Calm, clear	25	10.99	32.27	24.68
Aug 5	5	9.92	32.10	24.72		45	10.92	32.36	24.76
14.10-13	20	9.88	32.10	24.73					

STATION	M	TEMP	SAL	σ_t	STATION	M	TEMP	SAL	σ_t
T2, Sept 3	0	14.7	28.87	21.35	5, Sept 4	75	7.94	33.30	25.96
	5	12.49	31.26	23.62		150	6.65	34.13	26.80
17.32-43	15	11.13	32.30	24.67					
Calm, clear	25	11.05	32.38	24.74	6, Sept 4	0	13.0	32.66	24.60
	45	10.53	32.48	24.93		5	12.65	32.77	24.76
					2.02-15	15	11.60	32.79	24.97
T3, Sept 3	0	12.9	30.90	23.26	H.W.1.40	35	9.52	32.97	25.47
	5	11.53	32.14	24.48		75	7.30	33.48	26.20
18.00-09	15	11.17	32.29	24.66		145	6.66	34.07	26.76
Calm, clear	30	10.73	32.41	24.83					
	50	10.22	32.57	25.04	7, Sept 4	0	12.7	32.54	24.57
					(G. Manan Bank)	5	11.60	32.70	24.90
T4, Sept 3	0	12.4	31.60	23.90	3.16-26	15	9.39	32.99	25.50
	5	12.10	31.74	24.06		30	8.97	33.08	25.64
18.30-40	20	11.09	32.38	24.74		50	7.81	33.31	26.00
	40	10.09	32.57	25.06					
	65	9.74	32.65	25.18	8, Sept 4	0	13.4	32.74	24.58
						5	12.84	32.74	24.69
T5, Sept 3	0	12.0	32.23	24.47	4.39-52	15	11.41	32.74	24.96
	5	11.49	32.29	24.60	Calm	35	8.60	32.99	25.63
19.00-10	20	10.50	32.52	24.95	H.W.1.40	75	7.19	33.39	26.15
Calm, clear	40	9.78	32.66	25.18		150	6.59	33.96	26.68
L.W.19.39	65	9.61	32.70	25.24					
					9, Sept 4	0	12.2	32.63	24.73
T6, Sept 3	0	14.5	32.23	23.97		5	11.59	32.74	24.93
	5	13.12	32.27	24.29	5.40-54	15	10.51	32.74	25.12
19.33-42	20	10.23	32.63	25.09		35	8.13	33.12	25.80
	50	9.65	32.75	25.28		75	7.55	33.35	26.07
	75	9.49	32.75	25.30		150	6.75	33.87	26.59
T7, Sept 3	0	14.7	32.18	23.88	10, Sept 4	0	10.5	32.81	25.18
	5	13.49	32.21	24.16		5	10.02	32.83	25.28
20.00-15	20	10.21	32.59	25.06	6.44-57	15	9.09	32.90	25.48
	50	9.38	32.79	25.35	Light SE	35	8.40	33.08	25.73
	100	8.93	32.79	25.42		75	8.16	33.26	25.90
						150	7.01	33.62	26.36
Frenchman's	0	13.0	32.16	24.22					
Bay, Sept 3	5	11.66	32.23	24.53	11, Sept 4	0	9.5	32.83	25.36
	15	10.92	32.29	24.70	(Off Brier I.)	5	9.42	32.83	25.38
17.23-44	30	10.61	32.32	24.78	8.11-22	15	9.23	32.90	25.45
Calm, clear	50	9.93	32.38	24.93	Calm	30	9.09	32.92	25.50
						45	8.94	32.95	25.55
1,(Petit Manan)	0	11.1	32.61	24.92					
Sept 3	5	10.46	32.61	25.03	L1, Sept 4	0	12.6	30.95	23.37
	15	10.26	32.61	25.06		5	11.80	31.20	23.71
20.47-58	30	10.04	32.66	25.14	6.16-28	15	11.24	32.09	24.49
	50	9.81	32.70	25.21	Calm, clear	30	10.90	32.25	24.67
					L.W.8.01	50	10.08	32.48	25.00
2, Sept 3	0	10.0	32.63	25.13					
	5	9.93	32.66	25.16	L2, Sept 4	0	12.6	31.18	23.54
21.35-46	15	9.89	32.66	25.16		5	11.92	31.74	24.10
Calm, clear	35	9.90	32.66	25.16	6.49-58	15	11.38	32.20	24.55
	75	9.41	32.75	25.32		30	10.88	32.32	24.74
						50	10.49	32.47	24.92
3, Sept 3	0	10.6	32.70	25.07					
	5	10.03	32.75	25.22	L3, Sept 4	0	12.6	31.64	23.90
22.27-38	15	9.11	32.84	25.44		5	12.31	32.16	24.35
	35	8.97	32.92	25.52	7.18-30	20	10.47	32.43	24.89
	75	8.90	32.95	25.56	Calm, clear	40	9.42	32.68	25.26
						75	8.96	32.77	25.40
4, Sept 3	0	11.75	32.52	24.73					
	5	10.84	32.59	24.95	L4, Sept 4	0	13.6	31.96	23.94
23.42-56	15	9.79	32.66	25.18		5	12.94	32.25	24.30
	35	9.05	32.84	25.45	7.54-8.05	20	9.44	32.63	25.22
	75	7.52	33.39	26.10	Light NE	40	9.13	32.77	25.37
	150	6.57	34.14	26.83		90	8.74	32.79	25.45
5, Sept 4	0	12.0	32.63	24.77					
	5	11.94	32.63	24.78					
0.41-54	15	10.78	32.77	25.10					
Clear	35	8.70	33.06	25.66					

STATION	M	TEMP	SAL	σ_t
L5, Sept 4	0	13.9	32.01	23.92
	5	13.28	32.14	24.14
8.31-43	20	9.19	32.74	25.33
Light NE	50	9.06	32.77	25.39
Clear	100	8.40	32.90	25.58
L6, Sept 4	0	14.9	32.00	23.70
	5	14.70	32.01	23.75
9.08-20	20	10.83	32.48	24.87
NE, clear	50	8.70	32.92	25.56
	100	8.44	32.94	25.61
12, Sept 6	0	10.6	32.66	25.04
(Off Prim Pt)	5	10.51	32.66	25.06
8.29-40	15	10.42	32.66	25.08
Fresh SSW	30	10.37	32.68	25.10
Overcast,fog	50	10.29	32.68	25.12
13, Sept 6	0	11.2	32.63	24.92
	5	11.12	32.63	24.93
9.24-34	15	10.04	32.70	25.17
SSW, fog	35	9.84	32.74	25.23
L.W.9.40	75	9.61	32.77	25.30
14, Sept 6	0	13.0	32.25	24.29
	5	12.96	32.25	24.30
10.25-35	15	11.96	32.32	24.54
Fresh SWxS	35	9.37	32.77	25.33
Fog	75	8.84	32.86	25.49
15, Sept 6	0	13.4	32.09	24.08
	5	13.32	32.10	24.11
11.29-46	15	10.60	32.25	24.72
	30	9.40	32.66	25.24
	52	8.83	32.81	25.45
	95	8.20	33.12	25.79
16, Sept 6	0	13.3	32.18	24.17
	5	13.29	32.18	24.17
12.38-50	15	11.94	32.27	24.50
Fresh SWxW	35	9.24	32.74	25.33
Fog	75	8.00	33.13	25.83
	125	7.78	33.17	25.89
17, Sept 6	0	13.6	32.14	24.08
	5	13.57	32.16	24.11
13.46-59	15	12.06	32.29	24.50
Fresh SW,fog	35	9.02	32.83	25.44
	70	7.93	33.06	25.78
	132	7.58	33.24	25.98
18, Sept 6	0	13.6	32.14	24.08
	5	13.49	32.18	24.13
14.57-15.07	15	12.87	32.25	24.31
H.W.15.39	35	9.47	32.74	25.29
	75	8.06	33.01	25.72
19, Sept 7	0	10.7	32.38	24.80
	5	10.68	32.38	24.81
7.31-41	15	10.44	32.43	24.90
Light SW	35	10.02	32.50	25.02
H.W.4.11	75	9.09	32.70	25.32
SC4, Sept 7	0	11.4	32.23	24.58
(Wolves Bank)	5	11.45	32.25	24.58
9.22-35	10	11.38	32.25	24.59
L.W.10.36	20	11.11	32.27	24.66
	40	10.71	32.38	24.80
SC3, Sept 7	0	11.4	32.27	24.60
	5	11.07	32.29	24.67

STATION	M	TEMP	SAL	σ_t
SC3, Sept 7	15	11.01	32.29	24.68
10.03-15	35	10.80	32.38	24.79
Calm, cloudy	70	8.64	32.86	25.52
	120	8.37	32.95	25.64
SC2, Sept 7	0	11.8	32.23	24.50
	5	11.27	32.27	24.63
10.44-56	15	10.89	32.36	24.76
Calm	30	10.36	32.43	24.91
	60	9.61	32.63	25.19
	110	8.46	32.94	25.60
SC1, Sept 7	0	11.6	32.27	24.57
	5	11.27	32.29	24.64
11.30-42	15	10.85	32.38	24.78
Light NW	35	10.30	32.47	24.95
Mostly cloudy	75	9.32	32.70	25.29
CS1, Sept 8	0	12.9	32.07	24.17
	5	12.50	32.07	24.24
11.00-12	15	12.28	32.12	24.33
Calm, cloudy	30	11.96	32.21	24.46
	50	11.69	32.30	24.57
CS2, Sept 8	0	12.2	32.30	24.47
	5	11.87	32.30	24.54
12.23-34	15	11.31	32.48	24.78
Calm, cloudy	30	11.07	32.52	24.86
	60	11.05	32.52	24.86
CS3, Sept 8	0	11.0	32.65	24.97
	5	10.79	32.65	25.00
13.45-55	15	10.69	32.65	25.02
	30	10.66	32.68	25.05
	60	10.60	32.68	25.06
CS4, Sept 8	0	11.0	32.66	24.98
	5	11.00	32.66	24.98
ExS, cloudy	15	10.93	32.66	24.99
15.08-18	30	10.94	32.66	24.99
	40	10.94	32.66	24.99
FH4, Sept 8	0	11.3	32.65	24.91
	5	11.29	32.65	24.91
16.21-31	15	11.29	32.65	24.91
Cloudy	30	11.26	32.65	24.92
	50	11.25	32.65	24.92
FH3, Sept 8	0	11.8	32.50	24.70
	5	11.87	32.50	24.69
17.14-24	15	11.88	32.50	24.69
Moderate ExS	30	11.88	32.50	24.69
Cloudy	60	11.90	32.50	24.69
FH2, Sept 8	0	12.5	32.27	24.40
	5	12.55	32.27	24.39
18.06-15	20	12.56	32.29	24.40
E, cloudy	40	12.51	32.29	24.41
FH1, Sept 8	0	13.3	31.98	24.01
	5	13.31	31.98	24.01
19.11-22	15	13.30	31.98	24.01
Fresh ExN	40	12.68	32.16	24.28
5, Sept 12	1	12.77	32.07	24.00
	7	11.36	32.30	24.63
17.06-29	20	11.18	32.30	24.66
Light N,clear	40	10.78	32.45	24.85
L.W.16.00	75	9.71	32.70	25.22

STATION	M	TEMP	SAL	σ_t	STATION	M	TEMP	SAL	σ_t
M1, Sept 29	0	11.3	32.50	24.80	MC2, Sept 29	0	11.0	32.50	24.85
(Machias-Seal)	5	11.17	32.52	24.84		5	10.96	32.50	24.86
	10	11.14	32.52	24.84	15.16-38	10	10.94	32.50	24.86
16.32-52	20	11.09	32.52	24.85		20	10.97	32.50	24.85
W, clear	40	10.99	32.52	24.87		35	10.96	32.52	24.88
Heavy swell	75	10.98	32.54	24.88		70	10.98	32.52	24.87
M2, Sept 29	0	11.4	32.47	24.76	MC3, Sept 29	0	11.0	32.50	24.85
	5	11.16	32.50	24.82		10	10.94	32.54	24.89
15.45-16.05	10	11.00	32.54	24.88	16.23-40	20	10.93	32.54	24.89
W, clear	20	10.86	32.54	24.90		35	10.93	32.54	24.89
L.W.16.52	40	10.78	---	---		70	10.94	32.54	24.89
	75	10.77	32.56	24.94					
M3, Sept 29	0	11.1	32.56	24.88	MC4, Sept 29	0	10.9	32.56	24.91
	5	11.09	32.56	24.88		10	10.93	32.56	24.91
15.03-16	10	10.87	32.56	24.92	17.03-12	20	10.91	32.56	24.91
W, clear	15	11.01	32.56	24.90	Light NE	40	10.93	32.56	24.91
	40	---	32.61	---	Clear	75	10.91	32.56	24.91
M4, Sept 29	0	10.8	32.57	24.94	MC5, Sept 29	0	10.9	32.56	24.91
	5	10.69	32.57	24.96		5	10.92	32.56	24.91
14.27-39	10	10.69	32.57	24.96	17.37-46	10	10.90	32.56	24.91
W, clear	25	10.65	32.57	24.97		25	10.92	32.56	24.91
	50	10.70	32.57	24.96		50	10.89	32.59	24.94
MC1, Sept 29	0	11.2	32.47	24.80					
	5	11.00	32.47	24.83					
14.39-50	10	11.00	32.48	24.84					
W, clear	25	11.00	32.48	24.84					
Heavy swell	50	11.00	32.48	24.84					

The Life-History and Morphology of *Chironomus hyperboreus*

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ABSTRACT

In lakes of Saskatchewan adults emerge in late May and early June. Eggs, deposited over lake surface, sink to bottom. Larvae in soft bottom ooze (10-20 m. depth) grow rapidly in late summer, but little during rest of year. Four larval instars and two-year life-cycle. Larva and pupa described and additions made to Staeger's description of adult.

INTRODUCTION

In the summer of 1930 the writer began a general study of the Chironomidae in the lakes of the Prince Albert National Park. The species *Chironomus hyperboreus* was found to be particularly abundant in Waskesiu lake, and since its immature stages had not been described and little was known about the adult, it was decided to make it the subject of a special study.

The first portion of the paper deals with the anatomy of the four stages— egg, larva, pupa and adult. Since the larvae of this species resemble those of *C. plumosus* rather closely, a few drawings of the latter species are included for purposes of comparison. In the description of the immature stages the papers of Goetghebuer (1928) and Malloch (1915) were most useful, while Edwards' paper on the British non-biting midges (1929) was used as a guide in the description of the adult.

The writer wishes to express his appreciation to Dr. D. S. Rawson, under whose supervision most of the work was done. Thanks are due also to Dr. L. G. Saunders for aid in the anatomical studies. The identification of certain species was made by Dr. O. A. Johannsen of Cornell University, and the writer extends to him his sincere thanks.

METHODS AND EQUIPMENT

The chironomid larvae were collected with the Ekman dredge and the samples washed through three screens. The upper screen was of coppered wire mosquito netting and the lower two of silk bolting cloth, 480 and 1,400 meshes per square inch (645 sq. mm.) respectively. Most of the material was preserved in formalin, but in some cases a number of larvae were transferred to rearing jars.

Water temperatures were taken with the Negretti and Zambra reversing thermometer attached to a deep-sea water bottle. The dissolved oxygen was determined by Miller's method (De Laporte 1920).

In the study of the vertical distribution of the larvae in the bottom ooze, the heavy sampler, designed by Rawson (1930) for his study of the bottom fauna of lake Simcoe, was found to be useful.

DISTRIBUTION

Records of the distribution of *C. hyperboreus* appear to be very scanty. This may indicate a restricted distribution, or it may only mean that, since the immature stages were unknown, they have been classified with other species of the genus *Chironomus*. In either case we find no mention of *C. hyperboreus* in Edwards' British Non-Biting Midges (1929), in Malloch's Chironomidae of Illinois (1915), nor in Goetghebuer's Chironomaria (1928).

The species is found in Greenland, from where it was originally described by Staeger. According to information received from G. S. Walley of the Entomological Branch, Department of Agriculture, Ottawa, specimens have been taken at Victoria Beach, Manitoba, and at Royal Oak, British Columbia.

It is of interest to note that this species, although abundant in Waskesiu lake, Prince Albert National Park, is rarely found in the other lakes of the park. It seems to be adapted to the conditions existing in Lower Waskesiu lake, where it is not unusual to find as many as a thousand larvae per square metre. It is rarely found above the ten metre level and is most numerous at a depth of twenty metres.

LIFE HISTORY

In 1932 the first adult was caught in the evening of May 23. During the succeeding days the number of adults increased and they were soon found swarming in the evenings. The swarming reached its maximum on June 8 and 9, when dense "clouds" of adults were seen hovering near the shore at a height of approximately five metres above the surface of the ground or water. This height was observed to vary considerably with the weather conditions, for on calm evenings swarms rose to a height of approximately 10 metres, but when a light breeze was blowing off-shore these clouds descended to within a metre of the surface of the water.

During the heat of the day the adults found protection on the leaves of trees, usually on the shaded side. Here they remained until approximately one hour before sunset when they aggregated in swarms as described above. These swarms consisted almost entirely of males, only an occasional female being found. Occasionally a mating pair could be seen to leave the swarm and descend to the ground. It was of interest to note on four occasions that the mating pair consisted of a typical male and a gynandromorph, thus showing that, although the latter had typical male genitalia, it nevertheless exhibited female behaviour.

On the evening of June 9 the writer observed hundreds of females depositing their eggs on the lake, a considerable number even at a distance of several miles

from the shore. A similar occurrence was observed on Crean lake during the swarming of another species (*Pentapedilum* [*Sergentia*] *coracinum*) a week later. This widespread egg-laying would explain the more or less uniform distribution of the larvae on the bottom of the lake.

After being desposited, the egg masses sank to the bottom where they remained for a period of one or two weeks (depending upon temperature) before they hatched. In a study of the Chironomidae in general, Miall (1912) found that the eggs "float on the surface where they can get a fair supply of air, and run no risk of being smothered in silt or organic refuse. . . . These requirements are met in the case of *Chironomus* by laying the eggs in chains, and mooring them at the surface of the water." The writer observed this method of deposition in a species of *Glyptotendipes* which attach their eggs to aquatic vegetation. In the case of *C. hyperboreus*, however, egg masses were observed to sink immediately after being laid. On several occasions a gill net set at a depth of nine metres and left overnight at the time of a heavy adult emergence, had from thirty to fifty egg masses attached to it on the following morning.

In the rearing containers the eggs hatched in three days if kept in a warm room (temperature 20°C.), but this period was prolonged to six days if kept in a cool place (15°C.). The bottom lake temperature was approximately 10°C. at this time, and, therefore, eggs desposited during the first week in June would probably not hatch before the middle of June. The young larvae did not appear in the dredgings until the end of July, because larvae less than 5 mm. in length were washed through the screens.

Although the larvae were found on almost any type of bottom, they appeared to prefer a soft muddy ooze where they are supplied with abundant food and protection. Larvae of *C. hyperboreus* found on a shallow sandy bottom were always small in size and few in numbers. In this region there are found throughout the season such predaceous forms as *Cryptochironomus* and *Tanypus*. The latter especially is known to destroy them in considerable numbers, since Miall found "no fewer than seven heads of *Chironomus* larvae in the stomach of a single *Tanypus*."

According to Malloch (1915) the food of the larvae of the genus *Chironomus* consists of diatoms, green algae and other vegetable material. This was substantiated by an examination of the contents of the alimentary canal of larvae of *C. hyperboreus* from Waskesiu.

The feeding habits of chironomid larvae were studied by Leathers (1922). In the case of tube-dwelling forms, a group to which *C. hyperboreus* belongs, he found that they "were keeping a strong current of water flowing through their burrows." Possibly this current brought in and deposited particles that could be used as food. On several occasions, however, he found that the current was very weak, and when the tube was dissected under the microscope "the inner surfaces were found to be full of rounded holes." Since the writer has found larvae with burrows extending as far as twenty-five centimetres into the bottom mud, it seems quite likely that the usual method by which it obtains its food is similar to that of the earthworm. It is improbable that larvae in deep burrows could maintain a current strong enough to bring in food.

The larvae of *C. hyperboreus* were found to require two years to reach maturity. Although a number of species of Chironomidae are known to have several generations in a year, the writer has found no mention of the fact that any species takes two years to reach maturity. It is known that *C. plumosus* in Waskesiu lake has one generation every year, and it is difficult to understand why a species so closely related and living under similar environmental conditions should differ from it in this respect. The problem becomes more complex when we recall that *C. hyperboreus* emerges in the spring and the larvae are thus able to spend a longer period under conditions favouring rapid growth than the larvae of *C. plumosus*.

Throughout May and June two distinct groups of larvae of different lengths were found, as shown in table I. Group C consists of old larvae which emerged in the spring of 1932. It will be noticed that their numbers are decreasing steadily until at the beginning of July they have almost completely disappeared. Group B has an average length of approximately 8.5 mm. during the months of May and June. During the following months these larvae show considerable increase in length. The larvae of the "new brood"—group A—appeared in the dredgings for the first time on July 31 in comparatively large numbers. They were already over 5 mm. long. Apparently the screens were not of sufficiently fine mesh to retain smaller larvae. Fortunately the writer was able to rear a large number of larvae from eggs, and thus secured sufficient data to supplement those obtained from dredgings.

TABLE I.—Rate of growth of *C. hyperboreus* larvae, Waskesiu lake, 1932

Date	Two-year larvae, hatched 1930 Group C			One-year larvae, hatched 1931 Group B			New generation, hatched 1932 Group A		
	No. of larvae per six dredgings	Average length of larvae (mm.)	Standard deviation in length	No. of larvae per six dredgings	Average length of larvae (mm.)	Standard deviation in length	No. of larvae per six dredgings	Average length of larvae (mm.)	Standard deviation in length
May 14	73	17.64	5.04	49	8.20	1.40	..	....	....
May 27	22	16.91	5.66	17	8.71	1.07	..	....	....
June 9	18	16.0	2.45	37	9.05	1.01	..	....	....
June 16	..	....	....	..	....	....	*	1.0	*
June 23	14	19.0	1.28	30	8.60	.91	..	....	....
July 4	16	15.86	2.32	27	8.70	.81	..	....	....
July 6	..	....	....	..	....	....	*	3.60	*
July 11	..	....	....	86	8.83	1.11	..	....	....
July 29	..	....	....	..	....	....	*	4.60	*
July 31	..	....	....	27	12.30	3.48	67	5.45	.62
Aug. 7	..	....	....	..	....	....	*	6.30	*
Aug. 20	..	....	....	13	14.54	2.44	..	....	....
Sept. 5	..	....	....	148	13.82	1.64	156	8.22	1.36

*Not recorded. Larvae reared from eggs collected on June 8.

The data from table I are presented in the form of a graph (figure 1), in which three curves (A, B and C) are shown. Curve A indicates the growth of the larvae during the first season. There is a gradual increase in length in mid-summer, and by the first week in September the larvae have reached an average length of 8 mm. Practically no growth takes place during the winter months. Curve B shows the rate of growth of the larvae during the second season. These larvae would emerge the following spring. From curve C we deduce that no increase in the average length of the larvae takes place during the spring of the third year.

The larvae of *C. hyperboreus* undergo four ecdyses during their period of development. By accurate measurement of the width of the labium of sixty-eight larvae it was found that these individuals could be divided into four groups. All larvae from 4.5 mm. to 10.5 mm. in length had a labium approximately 12 mm. wide, while those longer than 10.5 had a labium .22 mm. wide. These two groups represent two instars. Applying Dyar's law it was found that by dividing the width of the labium of one instar by that of the preceding instar a factor was obtained which could be used to calculate the width of the labium of a larva in any other instar. It is thus clear that no instars were overlooked. The factor obtained was 1.8. Below are the calculated results and the results obtained by measurement.

Instar	Length of larva (mm.)	Observed width labium (mm.)	Calculated width labium (mm.)
1st............	-2.0	.04	.04 (.07:1.8)
2nd..........	2.0-4.5	.06	.07 (.12:1.8)
3rd..........	4.5-10.5	.12	.12 (.22:1.8)
4th..........	10.5-22.0	.22	

The mature *C. hyperboreus* larvae begin to pupate about the middle of May, shortly after the ice has left the lake. In the season of 1931 observations were begun on May 12, two days after the ice began to break up. The first dredgings were taken on May 14 and at this early date many were already preparing to pupate, as could be seen by the marked swelling of the thorax. While the factor or factors controlling the time of pupation are not yet understood, it seems un-likely that any inherent factor characteristic of the species is the sole determinant. Lundbeck, in his work on the North German lakes, found some evidence that an environmental factor, oxygen, might play an important part. Thus *C. batho-philus* was observed to emerge in the spring at a time when the oxygen content was increasing and the temperature of the water rising steadily, while *C. plumosus* emerged in the fall when the bottom oxygen was very low. This would suggest that in the former case a favourable condition, an abundance of oxygen, was an important factor, while in the latter an unfavourable condition, a decrease in oxygen.

"Es wäre also demnach das Schlüpfen des *Bathophilus* als durch optimale Bedingungen gefördert, das des *Plumosus* als durch ungünstige Bedingungen beschleunigt anzusehen." (Lundbeck 1926, p. 214).

A somewhat similar situation was found to exist in Waskesiu with respect to *C. hyperboreus* and *C. plumosus*. In 1933 the greatest number of larvae of *C. hyperboreus* pupated between May 17 and May 25, and during that period the bottom oxygen content rose from a trace to 6.5 p.p.m. *C. plumosus*, on the other hand, normally pupates in the latter part of July and the first week in August when there is commonly a marked decrease in bottom oxygen.

Comparatively few pupae were found in any of the dredgings even in the period preceding the maximum emergence. Since the development of the adult fly is almost completed in the pupating larva, a long pupal stage is unnecessary. Dredgings taken on May 22, 1932, showed that the number of larvae in the
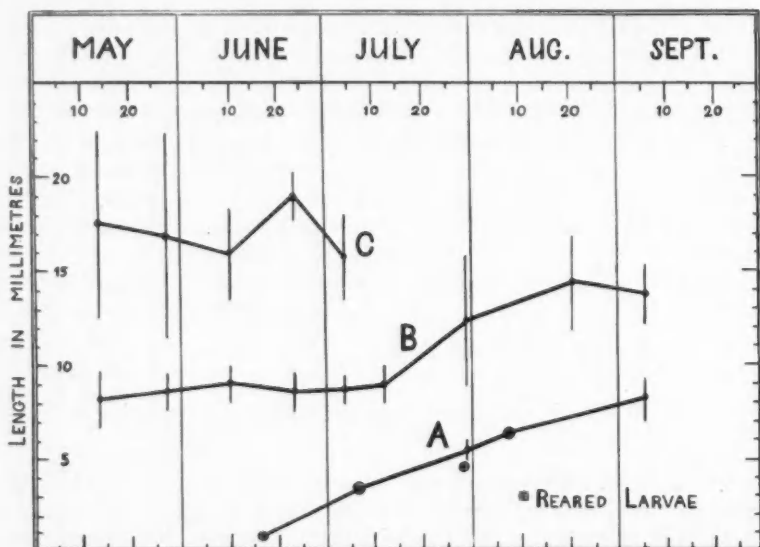
FIGURE 1. Rate of growth of *C. hyperboreus* larvae in Waskesiu lake, 1932.

pupating stage was still great, while on May 27 they had almost disappeared and still no pupae were found. It is possible, therefore, that the pupae rise from the bottom immediately after pupation.

MORPHOLOGY

THE EGG

The eggs are contained in a gelatinous mass secreted by the gluten gland. When this material comes in contact with the water it hardens, forming a protective coat. A mass may contain as many as 650 eggs arranged in a long winding strand so that the long axes of adjacent eggs are parallel. Traversing, and probably lending strength to, the whole mass, are two flexuous transparent threads which can be seen only with difficulty. The eggs are oval in shape and approximately .35 mm. long (figure 4E).

The Larva

Maximum length 22 mm. and colour blood red. Body consists of 12 segments—3 thoracic and 9 abdominal. First thoracic segment bears anterior prolegs with the curved bristles typical of this genus. 10th segment bears a lateral process (figure 2, C) approximately one-fifth as long as body segment. On 11th segment are two pairs of ventral blood gills which are longer than posterior prolegs, as shown in fig. 2, C. 12th segment bears two tubercles each with 5 long
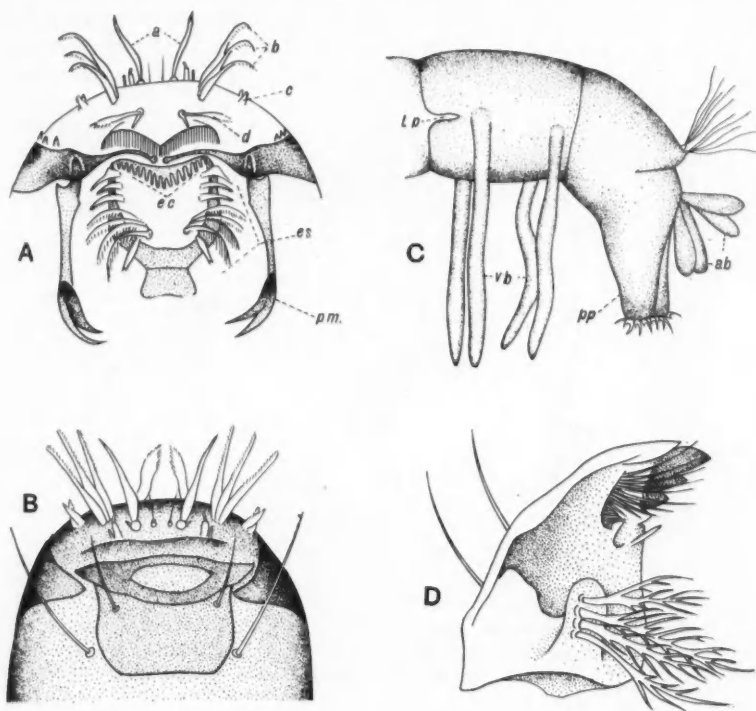

FIGURE 2. Larva of *C. hyperboreus.* A,—labrum, ventral view; B,—labrum, dorsal view; C,—last three abdominal segments; D,—mandible, dorsal view. *a-d*, setae on labrum; *ab*, anal blood gills; *ec*, epipharyngeal comb; *es*, epipharyngeal setae; *lp*, lateral process; *pm*, premandible; *pp*, posterior proleg; *vb*, ventral blood gills.

hairs, two pairs of anal blood gills, and the posterior prolegs each armed with two circles of setulae.

Head approximately one-half as long again as wide. Each epicranial plate bears two rudimentary eyes, upper somewhat smaller than lower; latter reniform with convex side directed forward, while former almost round in shape. Distance betwen eyes equal to longest axis of lower eye (figure 3, C).

On dorsal surface of labrum are several distinct groups of setae which may be described briefly as follows:

a setae (figure 2, A, B), swollen proximally but terminate in a rather sharp point distally, and arise from a small spherical base. Between them two simple hairs each originating from a flask-shaped protuberance. Lateral to setae are found two pairs of papillae.

b setae, three of these in a row on each side, have marginal fringe and unlike *a setae* do not arise from spherical base.

c setae, short, stout and fringed apically.

d setae, on latero-ventral surface of labrum, are blade-like with margins fringed distally, arise from spherical base with secondary sclerotized process.

On each side of labrum is a heavily sclerotized angular plate with several stout teeth along anterior margin. Medial angle tapers off gradually and the
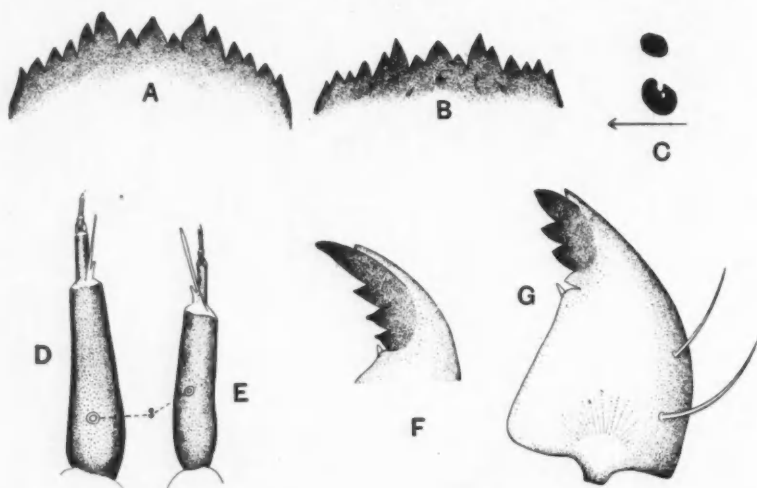
FIGURE 3. Larva. A,—labium, *C. plumosus*; B,—labium, *C. hyperboreus*; C,—left eyes, *C. hyperboreus*; D,—antenna, *C. plumosus*; E,—antenna, *C. hyperboreus*; F,—mandible, *C. plumosus*; G,—mandible, ventral view, *C. hyperboreus*; s, sensorium.

two shafts from the opposite plates approach each other in the mid-line just anterior to epipharyngeal comb.

Premandibles long and rod-like, each with three proximal prominences—middle one for articulation and others for muscle attachment; distal extremity bifurcated, each section terminating in a sharp point.

Epipharynx (fig. 2, A) consists of epipharyngeal comb and U-shaped sclerotized structure; former with 16 to 18 teeth which are blunt and rather separated at their bases. Teeth sharp in *C. plumosus*, their bases wide and close together, and their number seldom exceeding 14. Inside U-shaped piece are eight pairs of setae (figure 2, A, *es*), anterior pair "foot-shaped" and remainder with exception of eighth pair, blade-like with fringed margins. Figure 2, A is a ventral view and thus their blade-like appearance is not apparent. Last pair stout and slightly forked distally.

Mandibles (figure 2, D) triangular in shape and heavily sclerotized, with four teeth on distal part of inner margin; distal three black, but proximal always unpigmented in contrast to *C. plumosus* where all four black (figure 3, F). On dorsal surface are found: a large tooth always devoid of pigment; a group of 12 to 14 setae; a simple bristle just below mandibular teeth and four plumose bristles near the base (figure 2, D). Ventral surface bare except for two simple bristles on proximo-lateral margin.

Labium (figure 3, B) with one central and six lateral teeth; middle tooth trifid and median portion longer than lateral projections. Separation between
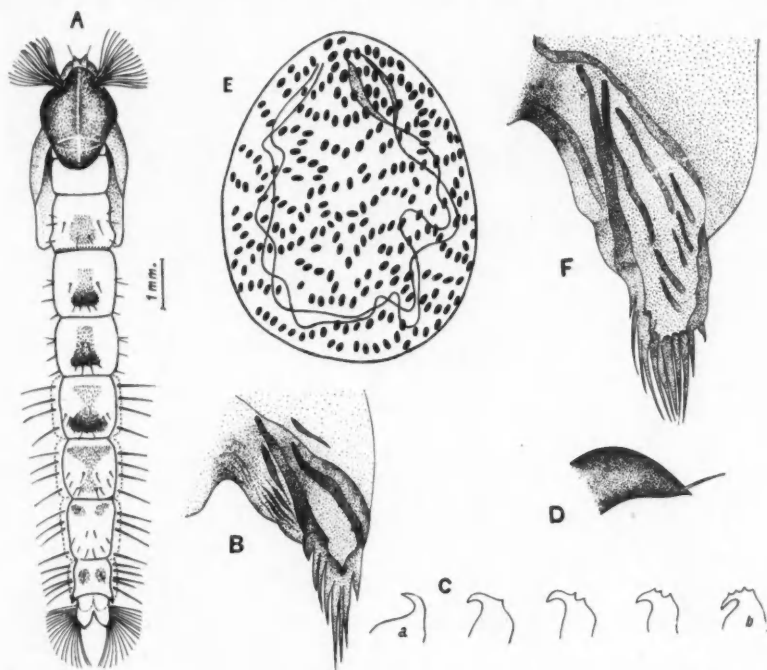
FIGURE 4. *C. hyperboreus*: A,—pupa (from exuvium); B,—lateral process of 8th segment; C,—series of setulae, *a* lateral to *b* median, distal margin of second abdominal segment; D,—frontal tubercle; E,—egg mass. *C. plumosus*: F,—lateral process of 8th abdominal segment.

first two lateral teeth slight. Fifth lateral tooth projects beyond 3rd, 4th and 6th. In *C. plumosus* (figure 3, A) lateral teeth all of similar height so that a straight line might be drawn through their apices.

Antenna (figure 3, E) 5-segmented, ratio of lengths of different segments being 40:10:3:5:1. Lateral bristle arising from distal end of basal segment as long as, or longer than, last four segments together. Sensorium in proximal half of basal segment, but in *C. plumosus* in proximal one-third of that segment (figure 3, D).

THE PUPA

Average length 12 mm. Colour bright red at first but darkening later and almost black shortly before emergence of the fly.

Dorsal surface of pupal head bears a pair of cone-shaped prominences, the frontal tubercles (figure 4, A). These are curved slightly downward at apices and terminate with a short seta (figure 4, D). On antero-lateral margin of thorax are the respiratory organs, each with stalk-like base and about four or five main branches. The latter divide into numerous slender colourless filaments. On dorsal surface of abdomen are numerous microscopic setulae, pale yellowish in colour. In segments 3, 4 and 5 they are stouter and more heavily sclerotized
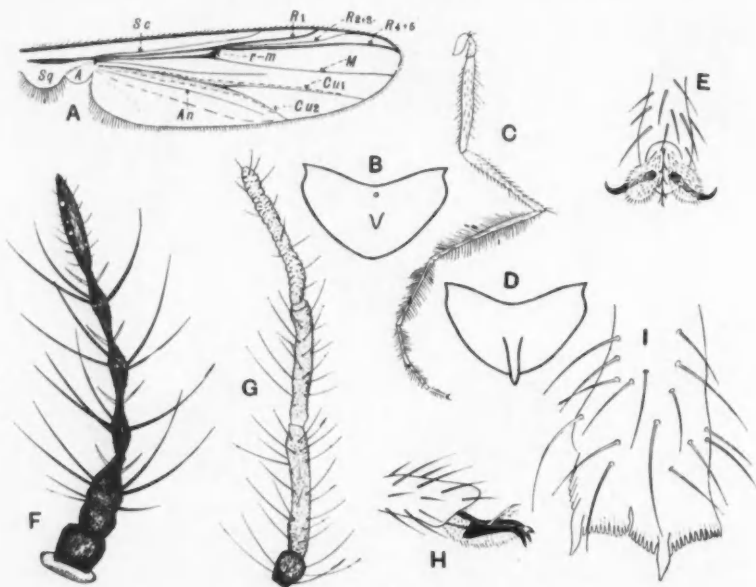
FIGURE 5. *C. hyperboreus.* A,—wing, male; B,—9th tergite, female; C,—front leg, male; D,—9th tergite, female; E,—last tarsal segment, ventral view; F,—antenna, female; G,—maxillary palp, male; H,—last tarsal segment, lateral view; I,—hind tibial comb. *A,* alula; *An₁,* first anal; *Cu₁,* first cubitus; *Cu₂,* second cubitus; *M,* media; *R₁,* first radius; *Sc,* subcosta; *Sq,* squama; *r-m,* radio-medial.

toward posterior margin of segments. The arrangement of these is of a distinct pattern in each segment (figure 4, A). Segment 2 bears on posterior margin about fifty yellowish spines, lateral ones curved and simple while medial ones have four teeth on dorsal curved margin. A complete gradation is found between these extremes as can be seen in figure 4, C. Segments 2, 3 and 4 bear on lateral margin 3, 4 and 4 small hairs respectively; segments 5, 6, 7 and 8 have 4, 4, 4, and 5 setae respectively. 8th segment has in addition a posterior lateral process on either side which terminates in eight rather long spines (figure 4, B). In

C. plumosus number of spines is about twelve, as indicated in figure 4, F. Last segment is bilobed with numerous flattened setae in a fan-like arrangement.

THE ADULT

In the following account additions have been made to the original description by Staeger and the illustrations used have been prepared by the writer.

Male 8 mm. in length. Antenna densely plumose and 12-segmented. Basal segments black, distal segment and bases of the plumose hairs brownish black.
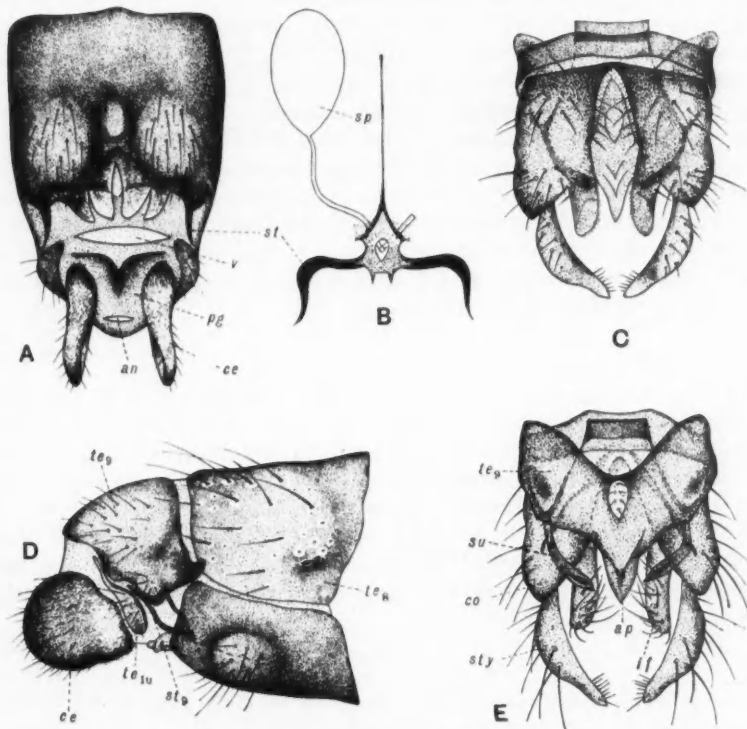

FIGURE 6. *C. hyperboreus.* A,—genitalia, female, ventral view; B,—9th sternite, female, ventral view; C,—hypopygium, male, ventral view; D,—genitalia, female, lateral view; E,—hypopygium, male, dorsal view. *an*, anus; *ap*, anal point; *ce*, cercus; *co*, coxite; *if*, inferior process; *pg*, post-genital plate; *sp*, spermatheca; *st*, sternite, *sty*, style; *su*, superior process; *te*, tergite.

Frontal tubercles present. Maxillary palpi brownish black, relative lengths of segments being 2: 7: 6: 8 (figure 5. G). Thorax black. Pronotum forms distinct collar and slightly emarginate along median line; scutal stripes barely visible. Abdominal segments black with gray apical margins; hairs on abdomen brown. Ninth tergite terminated by anal point. Coxite very stout and bears

two processes, a superior process, which is curved, heavily sclerotized and bare, and an inferior process which is broad, straight, with curved hairs, and projects beyond the coxite.

Wing (figure 5, A) with hairs on neither membrane nor veins M, Cu, and An_1. Fringe short except in region of anal angle and squama, absent in alula. R_1 curved up rather strongly at tip; R_2 meets costa approximately half-way between R_1 and R_{4+5}; cubital fork slightly beyond $r-m$. Halteres yellowish grey with tip of knob slightly darkened; base of peduncle brown. Legs black. Each hind tibial comb with short spur (figure 5, I).

Female resembles male in a general way. Antenna 6-segmented and very black with several sensoria on last segment. Legs dark brown. Proximal half of front femur somewhat yellowish. Front tarsus not bearded. Ninth tergite often with spur on dorsal surface (figure 5, B and D), which may be long, short, or absent altogether. Ninth sternite consists of two heavily sclerotized rods which meet in centre to form a bracket-shaped structure. Common opening of spermathecae in membranous portion between them (figure 6, B). A long, strongly sclerotized apodeme extends forward from membrane into cavity of 8th segment. Caudad to this is common opening of oviducts and gluten gland. Posterior to this again are the post-genital plate and anus, the latter bounded on either side by the somewhat saucer-shaped cerci.

GYNANDROMORPHS

A large number of gynandromorphic specimens belonging to the species *C. hyperboreus* were found. These had the body characteristics of a typical female, but the genitalia were of the male type. Upon dissection it was found that the ovaries had been destroyed completely, probably by a nematode worm which was commonly found in the body cavity of such forms, and that male reproductive organs were either in part or completely regenerated. It may be added that the problem is at present being investigated by the writer and the results already obtained are of sufficient interest to warrant the preparation of a separate paper.

SUMMARY

The account of the external anatomy includes a description and a number of drawings of the egg, larva, pupa and adult. Certain drawings of *C. plumosus* have been added since its larva resembles that of *C. hyperboreus*.

In following the life history of *C. hyperboreus* it was found that the adults swarm in the evenings during the last week in May and the first two weeks in June. The deposition of eggs is widely scattered over the lake surfaces even to a distance of three miles (4.8 km.) from shore. The eggs hatch in about ten days.

The larvae are found in soft bottom ooze at a depth of ten to twenty metres. Their food includes diatoms, green algae and other vegetable material. Growth is rapid during June, July and August and is almost negligible during the remainder of the season. The larva lives at the bottom of the lake for two years and during that period it passes through four instars.

Pupation begins about the middle of May and is probably stimulated by the spring circulation which commonly brings about a sudden increase in the temperature, and in the dissolved oxygen of the bottom water at this time of the year.

Gynandromorphism due to parasitism by nematode worms is common in *C. hyperboreus*.

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Further contributions to Mating in the American Lobster

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ABSTRACT

The male in copulation places a 5th pereiopod crosswise of the body in front of the first abdominal appendages as a support for the latter.

Mating can occur at least as late as 12 days after the female moults. Only part of the sperm supply is used by the female in fertilizing one batch of eggs.

THE MATING POSTURE

An additional detail has been observed in the mating posture as described by Templeman (1934). The first pair of male abdominal appendages which are inserted into the annulus of the female usually lie horizontally and pointing forward. They can be elevated to about 90° when a locking device prevents their being swung further back. On the two occasions when particular observations were made, the male in taking up the mating position was observed to pass one of his 5th pereiopods as far as possible across the body in front of the first pair of abdominal appendages and so that the pereiopod projected several inches on the other side of the body. The leg thus formed a support for the first abdominal appendages, elevating them and making them rigid enough to be inserted into the annulus of the female.

Exactly the same procedure has been observed by Andrews (1904) in the case of the crayfish, *Cambarus affinis*.

RELATIONS OF SHELL CONDITION IN FEMALE TO MATING

In experiments carried on by the author at Pte. du Chêne in 1932 (Templeman 1934) it was found that hard shelled male lobsters mated freely with soft shelled females which had moulted only a few hours previously. Of the 24 cases of mating then observed all occurred in less than 16 hours after the moulting of the female. The female is relatively helpless for several hours after moulting and if a male of suitable size is present mating will almost invariably occur.

Table I gives the results of an experiment carried on at St. Andrews, August and September, 1935, to determine the chance of unfertilized females mating some days or weeks after moulting. Mature female lobsters obtained from Caraquet moulted at various times between August 27 and September 21 in the absence of males. All the females except one had hatched their eggs a few weeks

223

before moulting. These females were placed immediately after moulting in a tank 6 feet (1.8 m.) long by 4 feet (1.2 m.) wide with running water about 2½ feet (0.8 m.) deep. The tank was in the basement at the Biological Station at St. Andrews, the room being illuminated with light from a doorway during the day and in complete darkness at night. The temperature of the water was about 13° to 15°C. during the course of the experiment.

In order to harden their shells as quickly as would occur in nature, the newly moulted females were allowed to eat the cast shell and small broken pieces of clam shell were added to the tank. Fresh herring was always present as food. This tank was also used for the mating experiment.

TABLE I. Success of mating with female lobsters in different conditions of shell

Total length cm.	When moulted	Condition of seminal receptacle of cast shell	Has carried eggs previously	When placed in presence of males	Condition of carapace Sept. 24	Condition of seminal receptacle of new shelled lobster, Sept. 24
23.5	Aug. 26-27	Sperms present	Yes	Sept. 20, 5 p.m.	Hard buckle	Empty
26.2	Sept. 2	"	"	"	Buckle	"
25.5	Sept. 7	"	"	"	Rubber	"
26.7	Sept. 8	"	"	"	Buckle	Sperms present
22.7	Sept. 9	"	Probably not	"	"	Empty
25.5	Sept. 11-12	"	Yes	"	Hard paper	"
31.1	Sept. 14	"	"	"	"	Sperms present
29.5	Sept. 15-16	"	"	"	"	Empty
26.8	Sept. 19	"	"	Sept. 22, 1 p.m.	"	Sperms present
25.2	Sept. 20	"	"	"	Soft paper	"
27.8	Sept. 21	"	"	"	Soft shell	"

Note.—All females removed from presence of males at 11 a.m., Sept. 24.

As observed in 11 cases where the annulus was dissected out from the cast shell the whole inner lining of the seminal receptacle is shed with the old shell, taking with it the hard gelatinous mass and the spermatophores which almost invariably plug the seminal receptacle in the case of mature female lobsters. The seminal receptacle in every lobster immediately after moulting is absolutely empty and devoid of sperms.

Two males used in the experiment were 24 cm., three 25 cm., three 27 cm., one 28 cm., one 31 cm., and one 33 cm. in total length. All the males were hard shelled and had been obtained from various areas in the southern part of the gulf of St. Lawrence. All were presumably mature since normal sperms were invariably found in the seminal vesicles of 10 males of 19 to 21 cm. from the Caraquet region, and the size at which lobsters mature is approximately the same over the whole of the southern part of the gulf. These males also, as determined by previous experiments (Templeman 1934) were of suitable size for fertilizing the females used.

Eight females which moulted between August 26 and September 16 were placed in the presence of these 11 males on September 20. Only two of these

females, one moulting 12 days and one 6 days before adding the males, were fertilized when the females were dissected on September 24. In the 6 remaining females which had moulted 5 to 25 days before being placed in the presence of males, the seminal receptacle was empty after being in the presence of males for 4 days. Three other females of similar size to the unfertilized ones were added to the group on September 22. These three females had moulted only one to three days previously and when dissected on September 24 all three were fertilized.

It is concluded that the normal time for mating of the female lobster to occur is within a few hours or days immediately after she has moulted, and although we have shown that an occasional mating can occur at least 12 days after moulting it is probable that most female lobsters which are not fertilized within the first few days of moulting will remain unfertilized until after the next moult. A further experiment with still harder shelled females than those used in the above experiment is necessary to settle the question absolutely.

RETENTION OF SPERMS BY EGG-BEARING FEMALES

Bumpus (1891) and Herrick (1911) reported the presence of sperms in the seminal receptacle of egg-bearing female lobsters and the latter concluded that since the eggs are rarely laid before the female becomes hard shelled (following a moult) the sperm had been acquired by copulation after the eggs were laid and when the females were in the hard shelled condition. Bumpus says, "Whether her supply is regularly and periodically renewed or whether she is impregnated once for all I am unable to decide".

Thirteen females which had borne external eggs for 10 to 11 months and were nearly ready for hatching were dissected at St. Andrews in 1934 and 7 with eggs similarly well developed in .1935. All these 20 lobsters had the seminal receptacle filled with the usual hard gelatinous substance with a mass of spermatophores embedded at the bottom. On microscopic examination millions of apparently normal sperms were found present in the spermatophores within each seminal receptacle.

A number of mature female lobsters were retained in a tank at St. Andrews and kept entirely apart from male lobsters during the course of the experiment. Five females laid a full supply of eggs while in the tank. These eggs were allowed to develop and all were fertile. Three of the females were dissected two weeks and two about nine weeks after the eggs were laid. In each case the seminal receptacle was filled with hard gelatinous substance with spermatophores containing millions of sperms normal in shape at the bottom. Thus female lobsters can lay a normal supply of eggs, fertilize them from the stock of sperms in the seminal receptacle and still have so many sperms left that we were unable to tell the difference between the contents of the seminal receptacle of a lobster which had laid and fertilized eggs and those of a female in which none of the sperm had been so used.

Even if males had been present with these females after they had laid their eggs no further transference of sperm could have been possible since the gelatinous material filling the seminal receptacle was entirely too hard to permit the introduction of the male copulatory appendages.

Although as a general rule a female lobster moults shortly after the hatching of the eggs and there is no case on record of a lobster's laying several batches of eggs between two successive moults, the above data undoubtedly indicate that a single copulation can provide sperm only part of which is used to fertilize the first batch of eggs, and in the case of the very large females with slow growth it is quite possible that several batches of eggs may be laid and fertilized between successive moults by sperm from a single copulation.

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